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Significance of Size Reduction in Solid Waste Management. Volume 3. Effects of Machine Parameters on Shredder Performance

Cal Recovery Systems, Inc.
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SIGNIFICANCE OF SIZE REDUCTION IN SOLID WASTE MANAGEMENT
Volume 3 - Effects of Machine Parameters on Shredder Performance

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16. ABSTRACT

Hammermill shredders for size reduction of refuse were examined at three sites to determine the influence of key machine parameters on their performance. Internal machine configuration and single- versus two stage size reduction were studied. Key parameters that were investigated and could be related to performance include the number and volume of hammers, open volume fraction, hammer tip speed, grate opening, open volume, and closed volume. The machine parameters were related to throughput, mill holdup, specific energy requirements, power draw, and product size using test data and curve fitting analysis. Studies of both actual and hypothetical scenarios of single- and multiple-stage size reduction indicated that internal machine configuration and degree of size reduction can significantly affect energy requirements for refuse size reduction.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to: a) prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; b) preserve and treat public drinking water supplies; and c) minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

This report is the last in a three-volume series of comprehensive studies dealing with the size reduction of solid waste. Data presented here show how machine parameters affect single- and multiple-stage size reduction. Data collected from three field tests were combined with data from previous studies to develop a procedure for optimizing shredder system performance.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Hammermill shredders for size reduction of refuse were examined at three sites to determine the influence of key machine parameters on their performance. Internal machine configuration and single- versus two-stage size reduction were studied. Key parameters that were investigated and could be related to performance include the number and volume of hammers, open volume fraction, hammer tip speed, grate opening, open volume, and closed volume. The machine parameters were related to throughput, mill holdup, specific energy requirements, power draw, and product size using test data and curve fitting analysis. Studies of both actual and hypothetical scenarios of single- and multiple-stage size reduction indicated that internal machine configuration and degree of size reduction can significantly affect energy requirements for refuse size reduction.

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LIST OF ABBREVIATIONS, SYMBOLS, AND CONVERSION FACTORS

ABBREVIATIONS

cm	-- centimeter
kg	-- kilogram
kWh	-- kilowatt-hour
kWh/Mg	-- kilowatt-hours per megagram
m	-- meter
MC	-- air-dry moisture content
Mg_d	-- megagrams on an air-dry weight basis
Mg_w	-- megagrams on a wet (as-received) basis

SYMBOLS

D_o	-- grate spacing
E_o	-- specific energy requirement (net) on an air-dry weight basis ($E_o = P_N/\dot{m}_d$)
$\bar{E}_o$	-- average specific energy requirement (net) on an air-dry weight basis
E_{o_w}	-- specific energy requirement (net) on a wet weight basis
$\bar{E}_{o_w}$	-- average specific energy consumption (net) on a wet weight basis
F_o	-- characteristic feed size
H	-- uncorrected shredder holdup
H*	-- corrected shredder holdup
L	-- conveyor belt length
$\dot{m}$	-- mass flow rate (general)
$\dot{m}_d$	-- mass flow rate (throughput) on an air-dry weight basis
$\bar{\dot{m}}_d$	-- average mass flow rate on an air-dry weight basis
$\dot{m}_w$	-- mass flow rate (throughput) on a wet basis
M	-- sample mass
N_H	-- number of hammers
P	-- power (general)
P_{FW}	-- freewheeling power
P_G	-- gross power

P_N -- net power ($P_N = P_G - P_{FW}$)

S -- hammer tip speed

v -- chart speed

V -- conveyor speed

V_C -- closed volume or volume of internal shredder hardware

V_H -- total hammer volume

V_S -- swept volume, or the cylindrical volume defined by the tip-to-tip diameter of the rotating hammers and the length of the shredder shaft within the shredding zone

V_O -- open volume ($V_O = V_S - V_C$)

V_{OF} -- open volume fraction

x -- particle size

X_O -- characteristic product size (screen size corresponding to 63.2 percent cumulative passing by weight)

$\bar{X}_O$ -- average characteristic product size

X_{90} -- nominal size (screen size corresponding to 90 percent cumulative passing by weight)

$\bar{X}_{90}$ -- average nominal product size

Z_O -- degree of size reduction, $(F_O - X_O)/F_O$)

$\bar{Z}_O$ -- average degree of size reduction

CONVERSION FACTORS

1 cm = 0.39 in.
1 m = 3.28 ft
1 kg = 2.20 lb
1 mg = 1.10 ton

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SECTION 1

INTRODUCTION

BACKGROUND

This study examines the performance of horizontal swing hammermills as a function of the fundamental machine parameters such as grate spacing, number of hammers, etc. The study is a logical extension of our earlier work [1,3] that defined fundamental comminution parameters and determined energy requirements as a function of the particle size distribution of the shredded product. Data was collected at refuse processing plants located at Appleton, Wisconsin; Odessa, Texas; and Richmond, California. This data together with information from earlier reports [1,2] formed the basis for the present investigation.

A previous evaluation of municipal solid waste shredders indicated that machine parameters could significantly influence the efficiency and performance of refuse size reduction equipment [3]. The study highlighted possible techniques for optimizing single- and multiple-stage shredding. The goal of the present study is to implement some of the recommendations presented in the previous evaluation and determine the influence of various machine parameters on energy consumption and particle size.

Prior to the present study, no analytical methods had been developed to correlate shredder performance with internal design. Consequently, even though throughput, product particle size, and the corresponding power requirements were known, the designer has had to rely on trial-and-error methods to determine the internal configuration needed to attain the required performance. The availability of an analytical method would reduce reliance upon the trial-and-error methods and could contribute to an improvement in shredder design.

The present study utilizes data from a number of shredding facilities. Throughput, mill holdup, power draw, specific energy, and product size are presented as functions of the the hardware components and the geometry of the shredder cavity. Where possible, trends and methods for general analysis have been identified so that performance may be predicted for other operating conditions. The machine parameters evaluated are those typically encountered in the industry (e.g., hammer tip speed, grate opening, and number of hammers) as well as newly defined volumetric terms (e.g., total hammer volume, closed volume, open volume, and open volume fraction).

A summary of the tests conducted for the size reduction study is presented in Table 1.

TABLE 1. SUMMARY OF TESTS CONDUCTED FOR THE SIZE REDUCTION STUDY[a]

Site	Test No.	Operating Conditions: Hammer Variations	Operating Conditions: Feed Size Variations	Operating Conditions: Grate Spacing Variation	Number of Measurements: Power Draw	Number of Measurements: Particle Size	Number of Measurements: Throughput	Number of Measurements: Holdup
Appleton, WI West Mill	1	24 Hammers	Raw MSW	12.7 cm x 30.5 cm	8	8	8	8
	2	40 Hammers	Raw MSW	12.7 cm x 30.5 cm	9	9	9	9
	3	64 Hammers	Raw MSW	12.7 cm x 30.5 cm	8	8	8	8
Odessa, TX	1	10 Hammers(F)[b]	Raw MSW	24.1 cm x 35.6	7	7	7	7
	2	10 Hammers(R)[c]	Raw MSW	24.1 cm x 35.6	6	6	6	6
	3	14 Hammers(R)	Raw MSW	24.1 cm x 35.6	8	8	8	8
Richmond, CA	1	44 Hammers	Raw MSW	10.2 cm x 10.2 cm	7	7	7	7
	2	44 Hammers	Prod. from Test No. 1	5.1 cm x 10.2 cm	8	8	8	8
	3	44 Hammers	Raw MSW	No grates used	7	7	7	7
	4	44 Hammers	Prod. from Test No.3.	5.1 cm x 10.2 cm	8	8	8	8

[a] All shredders are horizontal swing hammermills.

[b] F = forward rotation.

[c] R = reverse rotation.

One of the findings of a previous study [3] was that the number of hammers appeared to affect the specific energy requirement for size reduction. Specifically, the Newell shredder in Odessa, Texas, required less specific energy than other horizontal hammermills for equivalent size reduction. The difference in the energy requirement at the time of the first study was attributed to the relatively few hammers used in the Newell shredder (14 versus the 24 to 48 hammers used in the other hammermills).

To investigate the relationship between energy requirement and number of hammers, the present study included tests of two shredders with different numbers of hammers. The dependence of specific energy (kWh/Mg) on the number of hammers was established by: 1) measurement of energy consumption and product size for different numbers of hammers; and 2) measurement of mill holdup (the quantity of material in the shredder at any instant in time) as a function of material throughput.

A second finding of the previous study [3] concerned the possibility of optimizing the energy used in two-stage shredding, by considering it as an integrated system. Two factors indicate that two-stage shredding may not be optimized. First, data from the Ames plant showed that the secondary shredder uses approximately twice as much energy per ton processed as that used by the primary shredder. Second, the two-stage shredding operation at Ames required 50 to 100 percent more specific energy than that required for the single-stage shredding operation at the Baltimore County plant.

Due to the discrepancy between energy requirements for single- and two-stage size reduction, two multiple-stage configurations were field tested in the present study. The grate opening size was varied in each of the two multiple-stage configurations to assess its influence on energy consumption. The data were interpreted in terms of power draw, specific energy requirements, particle size, and throughput. In addition, data from earlier studies [2,5] were used to prepare a generalized procedure for analyzing specific energy requirements of single- and multiple-stage systems where other operating conditions and shredder types are under consideration.

SITE DESCRIPTIONS AND SHREDDER SPECIFICATIONS

Data for the present study were collected from resource recovery plants located in Appleton, Wisconsin; Odessa, Texas; and Richmond, California. Three dissimilar horizontal swing hammermills were selected for testing. The main components of this type of shredder are shown in Figures 1 and 2. Brief descriptions of the shredders and test procedures are as follows:

Appleton West

The Outagamie County Solid Waste Shredding Facility located in Appleton, Wisconsin, operates two Allis-Chalmers Model KH 12/18 horizontal hammermills (designated East and West) in parallel to shred approximately 160 tons of refuse received daily. Ferrous material is recovered after shredding using a magnetic belt conveyor, and the remaining shredded waste is compacted into transfer trailers and transported to landfill. Table 2 provides a summary of the principal features of the Appleton shredders, and a flow schematic for the Appleton facility is presented in Figure 3.

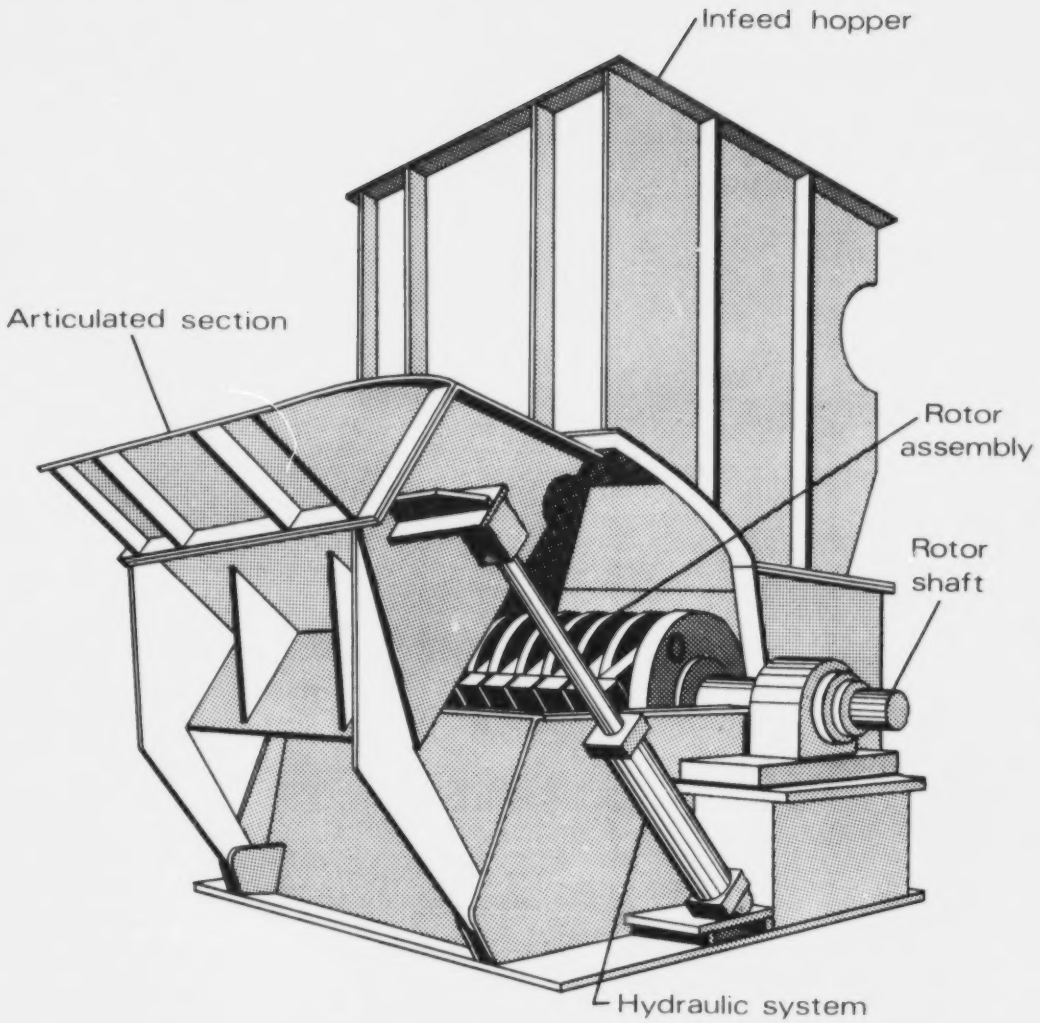

Figure 1. Horizontal swing hammermill.

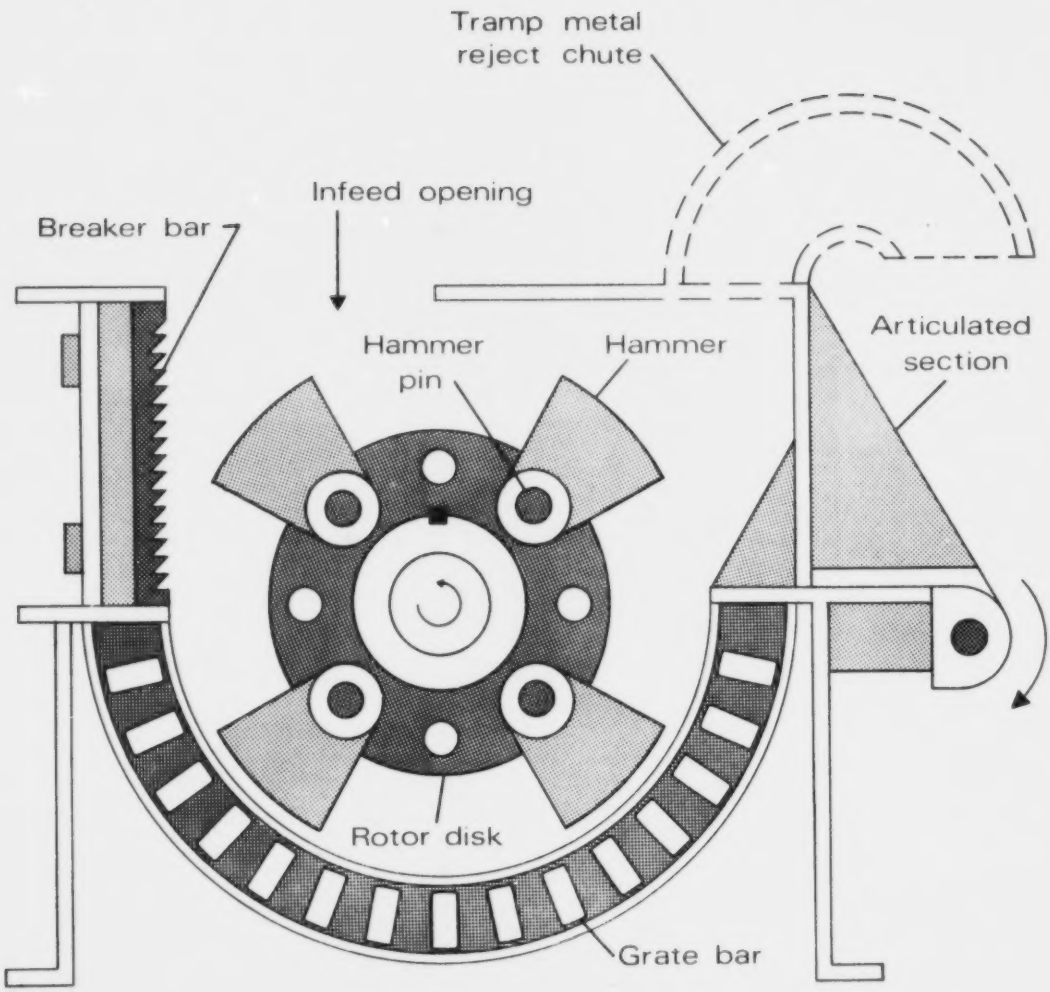

Figure 2. Horizontal swing hammermill
(cross-sectional view)

TABLE 2. APPLETON WEST SHREDDER SPECIFICATIONS

Item	Specification
Shredder	
Manufacturer	Allis-Chalmers
Model	KH 12/18
Grate opening (cm)	12.7 x 30.5
Number of hammers	48 (4 rows of 12)
Hammer mass (kg)	9
Hammer material	Carbon steel .4-.5% carbon
Tip to tip diameter (cm)	123
RPM	869
Drive	V-belt
Tip velocity (m/sec)	56.0
Motor	
Manufacturer	Allis-Chalmers
Model	114, Type G
RPM	1775
Rating (kW)	298
Voltage (volts)	480, 3 phase
Current (amps)	462

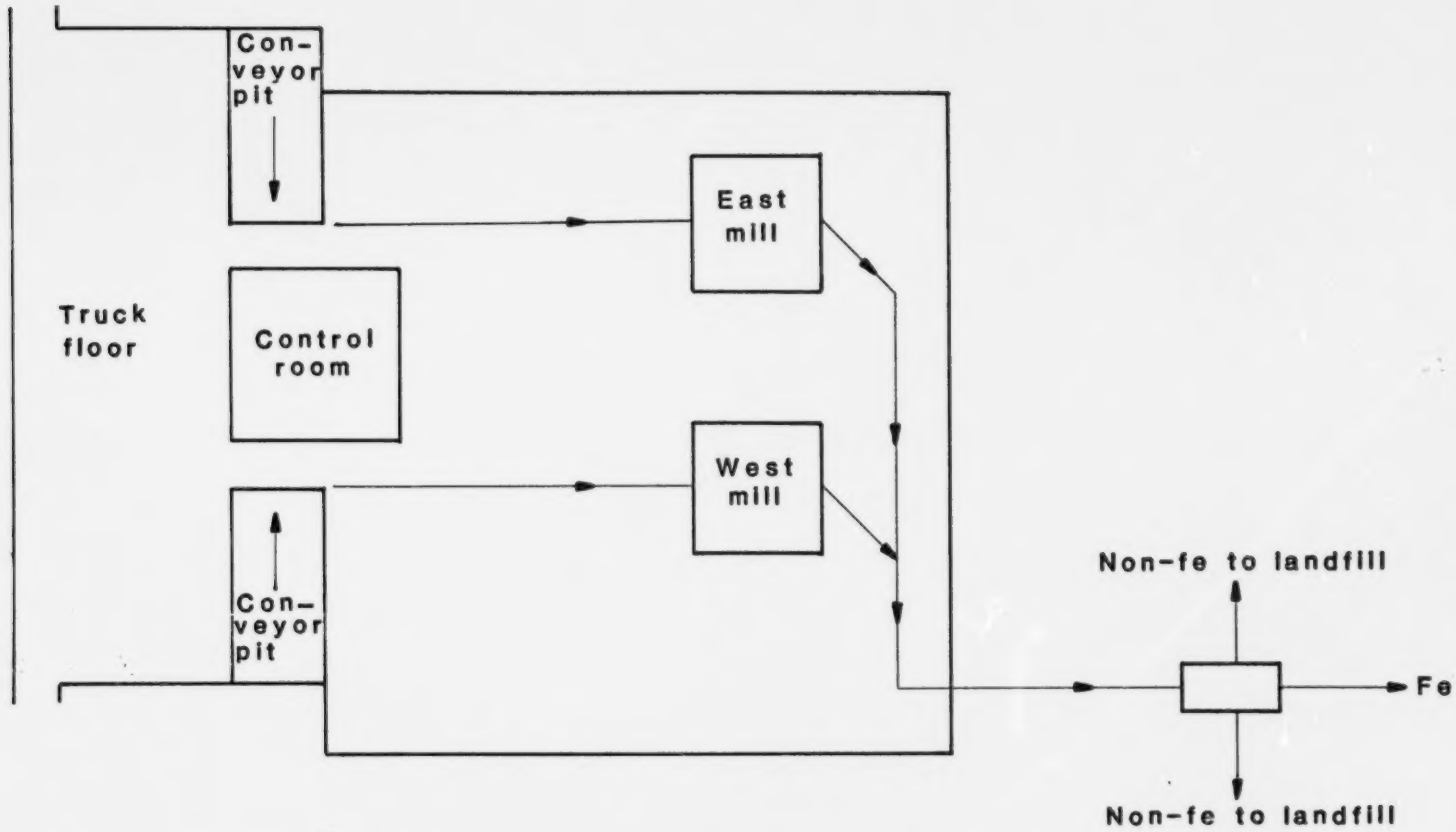

Figure 3. Flow schematic for Appleton facility.

Refuse trucks are weighed at the scale house as they enter and leave the site, thus maintaining a record of the total tonnage processed. After initial weighing, trucks enter the building and dump refuse into either one of two receiving pits, the floors of which are steel piano-hinged conveyors. Each receiving conveyor transports refuse to an inclined steel piano-hinged shredder input conveyor. Refuse is visually inspected while it is on the inclined conveyors by plant personnel, and any items which have proven difficult or dangerous to shred are removed. After shredding, the output from both shredders drops onto a horizontal rubber belt discharge conveyor which transports the shredded product to an inclined rubber belt conveyor for removal to the ferrous recovery station. After removal of the ferrous material, the remaining refuse is loaded into transfer trailers for transport to the landfill. For the present evaluation only the West mill was tested.

Odessa

The City of Odessa Solid Waste Management Facility, shown in Figure 4, has a single Newell Model 68 horizontal hammermill in operation. Approximately 230 tons of refuse are shredded on a typical day. The plant is equipped to recover ferrous material and pack the shredded refuse into transfer trailers for transport to the landfill. The major features of the Newell shredder are summarized in Table 3.

Records of the net tons of refuse entering the facility are maintained in the scale house. After weighing, trucks dump their contents onto the tipping room floor. A rubber-tired front end loader pushes the refuse from the tipping floor into either one of two opposing hydraulic push pits. As the moving wall of the push pit approaches the rubber belt feed conveyor, refuse is forced onto the belt. A small grapple is situated near the juncture of the push pits and feed conveyor in order to pick out hazardous items and help control the flow of refuse from the push pits. After shredding, the refuse is discharged onto a second rubber belt conveyor which transports the refuse to the ferrous recovery station. After ferrous removal, the refuse is dropped into a packer unit which packs the shredded product into transfer trailers for transport to the landfill.

Richmond

The University of California solid waste processing facility, located in Richmond, California, is a pilot-scale resource recovery plant capable of processing up to 15 Mg/h of MSW. The facility includes the following unit operations: size reduction, air classification, trommel screening, and ferrous recovery. A schematic of the processing line is shown in Figure 5.

The principal element of the size reduction module is a 190 kW horizontal swing hammermill. Its specifications are summarized in Table 4.

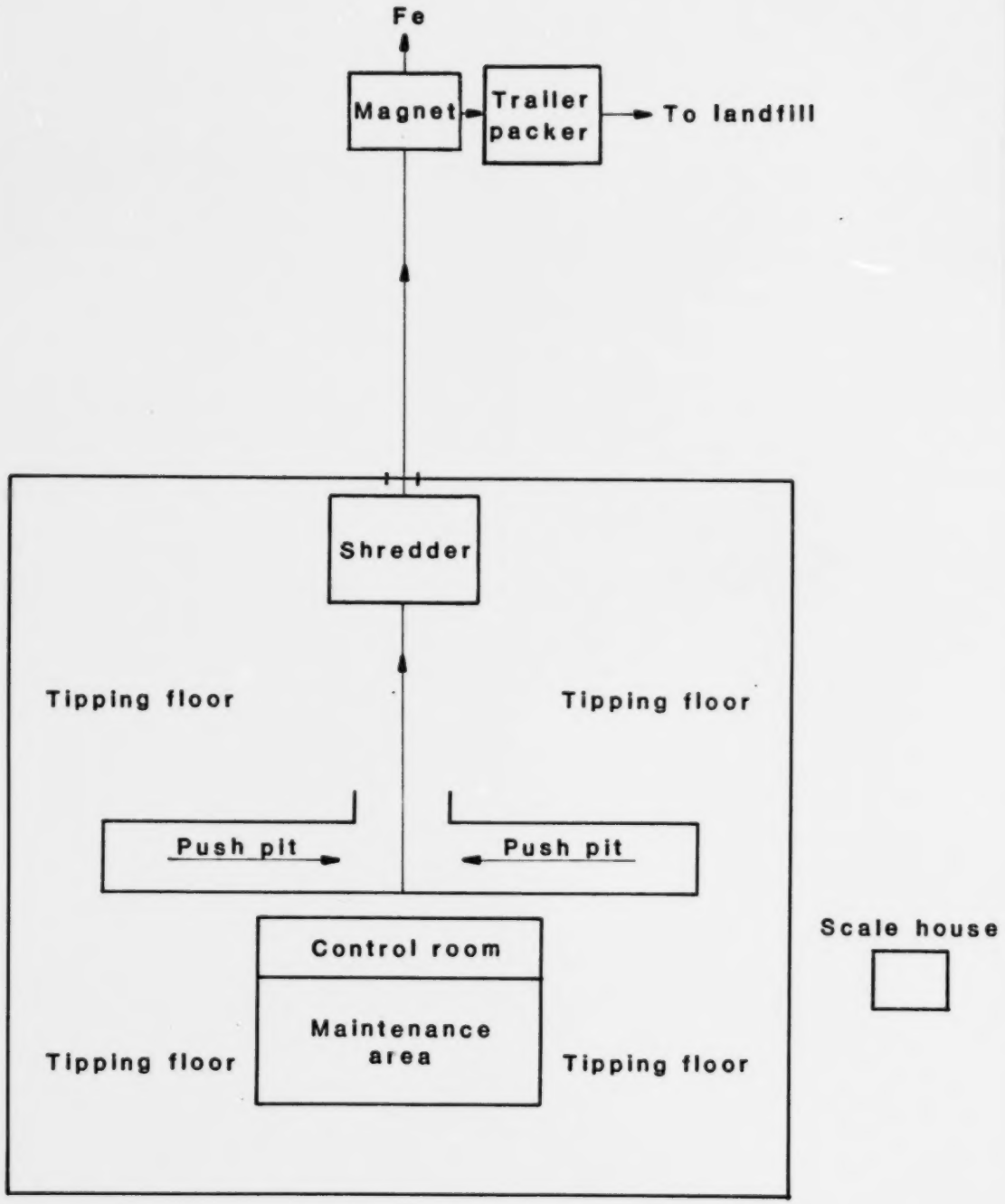

Figure 4. Flow schematic for Odessa facility.

TABLE 3. ODESSA SHREDDER SPECIFICATIONS

Item	Specification
Shredder	
Manufacturer	Newell
Model	68
Grate opening (cm)	35.6 x 24.1
Number of hammers	14
Hammer mass (kg)	67
Hammer type	manganese steel
Tip to tip diameter (cm)	150
RPM	880
Drive	direct
Tip velocity (m/sec)	69.1
Motor	
Manufacturer	Toshiba
Model	TIM-VCK-V
RPM	880
Rating (kW)	373
Voltage (volts)	2400, 3 phase
Current (amps)	295

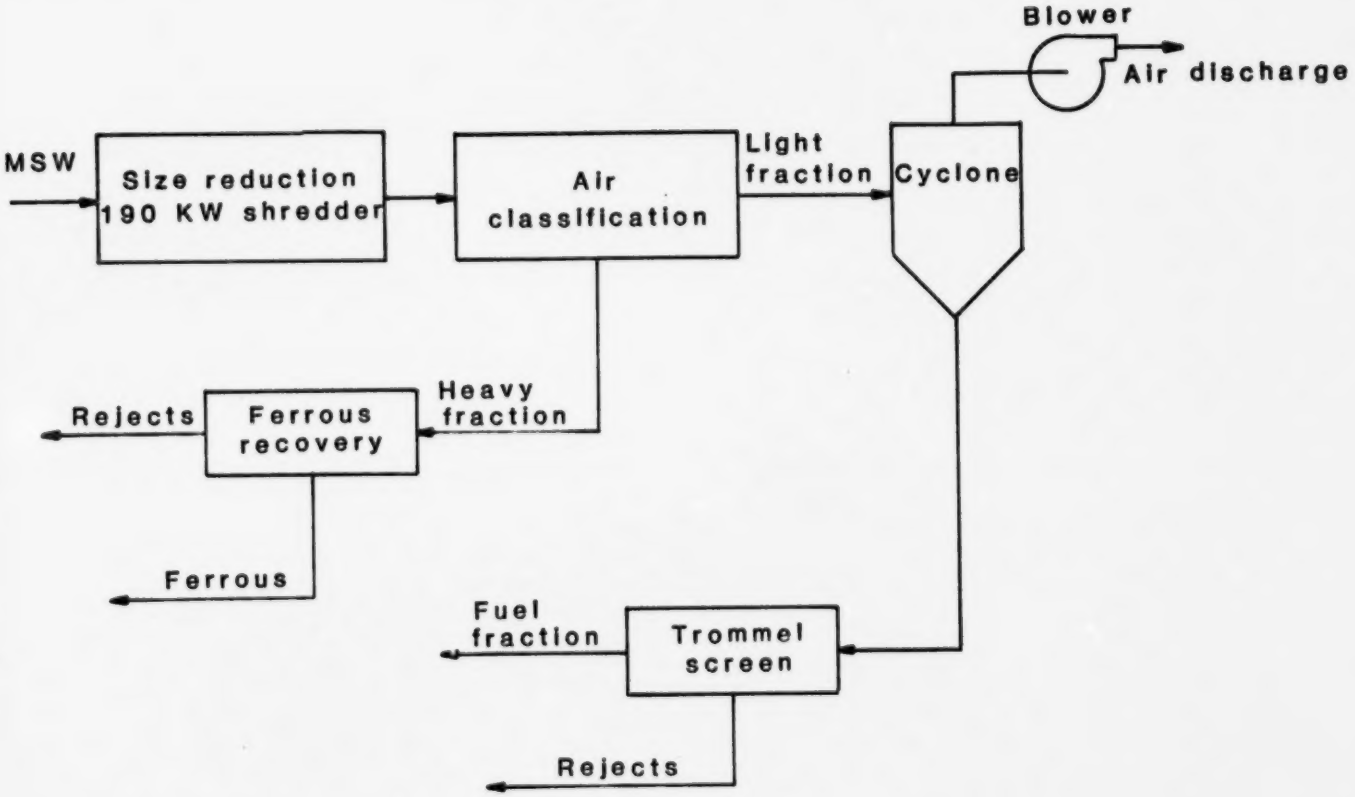

Figure 5. Flow schematic for Richmond facility.

TABLE 4. RICHMOND SHREDDER SPECIFICATIONS

Item	Specification
Shredder	
Manufacturer	Allis-Chalmers Gruendler
Model	48-4
Grate opening (cm)	12.7 x 30.5
Number of hammers	44 (2 rows of 10) (2 rows of 12)
Hammer mass (kg)	9
Hammer material	Manganese Steel
Tip to tip diameter (cm)	9.1
RPM	1200
Drive	V-belt
Tip velocity (m/sec)	57.5
Motor	
Manufacturer	Allis-Chalmers
Model	811
RPM	1200
Rating (kW)	190
Voltage (volts)	480, 3 phase
Current (amps)	300

SECTION 2

FINDINGS AND CONCLUSIONS

SPECIFIC ENERGY REQUIREMENTS

1. Using all available test data, the authors developed a plot of specific energy as a function of size reduction and grate spacing (Page 44). This plot forms the basis of a method to predict specific energy requirements for single- and multiple-stage size reduction.

2. Derived specific energy requirements of various single- and multiple-stage size reduction scenarios (Page 46) indicate that the net specific energy requirement for producing a characteristic particle size (X_o) between 2.0 and 0.85 cm is relatively low when using a flail mill as the primary shredder in combination with a secondary shredder having optimized grate spacing.

3. For small degrees of size reduction (i.e., for $X_o > 2.0$ cm), derived data (Page 46) indicates that single-stage size reduction has a lower net specific energy requirement than two-stage size reduction.

4. The most energy efficient system based on gross specific energy requirements (which includes freewheeling energy) was found to be single-stage size reduction using a 10.2 cm grate spacing. However, where large degrees of size reduction are required (i.e., $X_o < 1.2$ cm) single-stage size reduction may not be practicable. If this is the case, either single-stage reduction with a 5.1 cm grate spacing or two-stage reduction using a flail mill and a shredder with a 10.2 cm grate spacing may be the most energy efficient system (Page 46).

MACHINE PARAMETERS AND SHREDDER PERFORMANCE

1. Key parameters were identified and calculated to describe the internal configuration and performance of hammermills (Page 49).

2. A number of empirical equations for individual hammermills were developed (Equations 9 to 22). These equations relate throughput and mill holdup, power draw and mill holdup, and specific energy and product size. The equations are expressed in terms of machine parameters that characterize the internal configuration of the shredder cavity and operating parameters. The equations may be used to predict changes in shredder performance based upon changes in the machine parameters (e.g., number of hammers).

Analysis of data obtained from tests conducted of the Appleton West and Odessa sites resulted in the following findings and conclusions related to the number of hammers and shredder performance.

3. For throughputs in excess of 20 Mg/h, characteristic product size increased significantly as the number of hammers was decreased on the shredders tested (Page 56).

4. For a constant characteristic product size, net power requirement for size reduction tends to increase with a decrease in the number of hammers. For a constant throughput, the net specific energy requirement tends to decrease with an increase in the number of hammers. An increase in the number of hammers from 24 to 64 at the Appleton West Mill decreased the net power and specific energy requirement by as much as 30 percent. The corresponding increase in the freewheeling power requirement was relatively insignificant (Page 58).

5. The use of as few as ten hammers appears to be possible without adversely affecting shredder performance (Page 58).

SECTION 3

RECOMMENDATIONS

The use of a graphical procedure to determine specific energy requirements for size reduction is a convenient and inexpensive method for the selection of a single- or multiple-stage configuration. Additional field and laboratory test data would clearly improve the accuracy and predictive value of the graphical procedure presented in this study (Procedure IV, Section 6). More data are particularly needed for small degrees of size reduction, such as that which occur using a flail mill. Additional test work should therefore be conducted to provide these data.

SECTION 4

MATERIALS AND METHODS

POWER MONITORING INSTRUMENTATION

The power monitoring equipment includes a Scientific Columbus Model DL34-2K5A2-AY-6070 watt/watt-hour transducer, a Houston Instruments Model 3000 chart recorder, and a digital dividing circuit (Figure 6). Since the nominal inputs to the transducer are 75 to 135 volts and 0 to 6.5 amperes, transformers are required to reduce the line voltage and shredder current to these levels.

Two output signals are provided by the transducer. The first is an analog current signal which is directly proportional to power and may range from zero at no load to one milli-amp at full load with all three elements in use. A full load one milli-amp signal corresponds to 500 watts per element or 1500 watts total on the secondary (transducer) side of the current and potential transformers. The analog current signal is passed through a precision 1000 ohm resistor, which converts the current signal to a voltage signal. The voltage drop across the resistor is recorded on the chart recorder (Figure 7) to provide both a time base and a permanent, continuous record of the power requirements. The power required by the shredder can be found by multiplying the power levels measured on the secondary side of the monitoring equipment by the product of the potential and current transformer ratios, R_V and R_C, respectively.

The second transducer output is a digital signal directly proportional to energy. The transducer produces a constant internal count rate of 2160 counts per hour under the full load rating of 1500 watts. Dividing the full load rating (i.e., 1500 watts) by 2160 yields the number of watt-hours for each output pulse, (i.e., 0.694 watt-hours/pulse.) Multiplying the watt-hour/pulse content by the product ($R_V R_C$) of the potential and current transformer ratios yields the energy used on the primary side of the transformers. The digital signal is subsequently sent to the dividing circuit, which counts the pulses and triggers an event marker on the chart recorder after a predetermined number of pulses have been accumulated.

The general layout of the power monitoring equipment is presented in Figure 8. Transformer ratios used at each site are listed in Table 5.

OTHER EQUIPMENT

A digital stopwatch was used for making time measurements.

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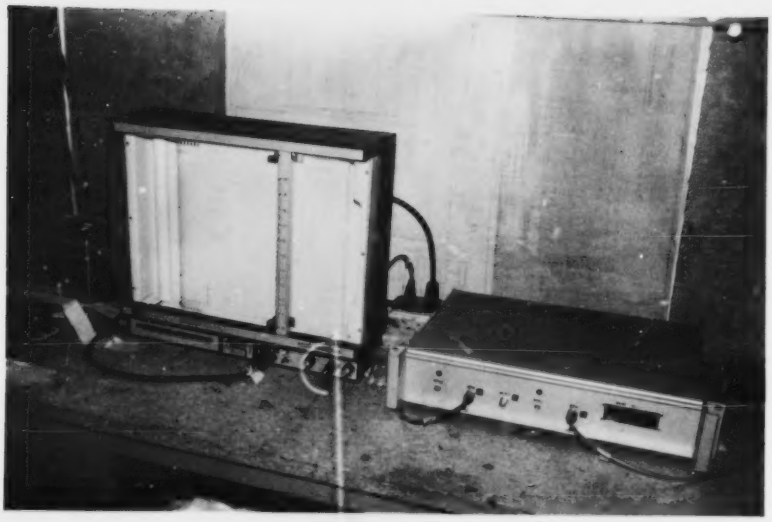


Figure 6. Watt/watt-hour transducer, left; chart recorder, center; divider, right.

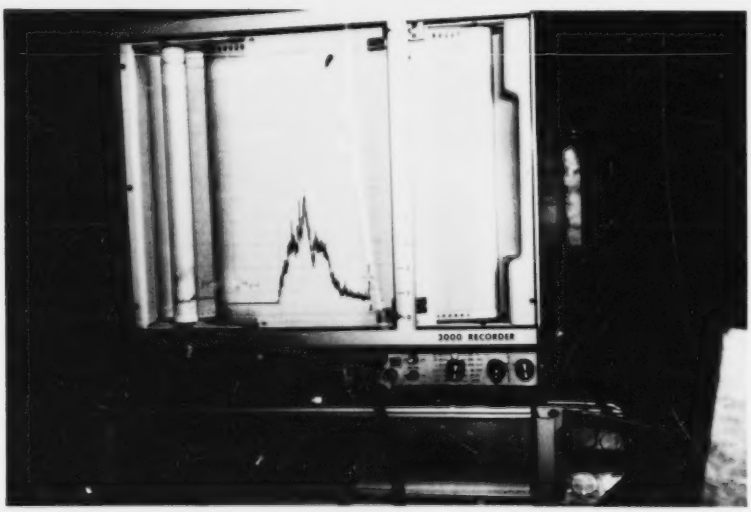


Figure 7. Chart recording of energy (top) and power (bottom).

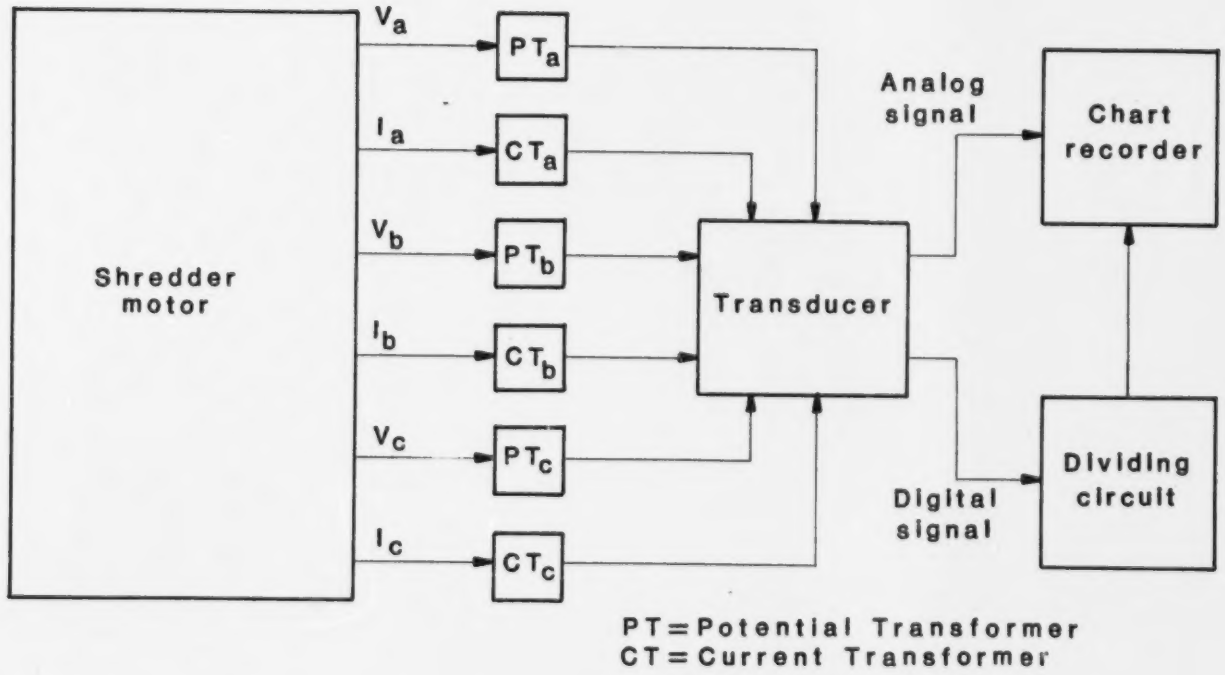


Figure 8. Schematic layout of power monitoring equipment.

TABLE 5. TRANSFORMER RATIOS USED AT EACH SITE

Site	Voltage Ratio, R_v	Current Ratio R_c	Product $R_v R_c$
Appleton	2.4:1	100:1	240:1
Odessa	20:1	60:1	1200:1
Richmond	2.4:1	60:1	144:1

Conveyor belt speeds were determined in most cases with a digital rpm gauge. An alternative method for determining belt speed was to measure the time necessary for the belt to traverse a known distance, and then divide the distance by the elapsed time.

In order to obtain size distributions for the shredded refuse samples, the samples were first screened on a set of manually held screens having square wire mesh openings of 20.32, 10.16, 5.08, and 2.54 centimeters. Screening of the undersize from the 2.54 centimeter hand held screen was carried out on a SWECO model LS 18533333 Vibro-Energy Rotary Screen.

SIZE DISTRIBUTION ANALYSES

The samples were weighed and air dried to constant weight in a drying room (ambient conditions, 22°C and 65 percent relative humidity) after which the samples were reweighed to permit determination of the air-dry moisture content. Size analyses of the samples were performed using both manual and mechanical screens. The dried refuse was placed on the largest of the manually held screens and shaken until no further refuse was observed to pass through the screen. The oversize from the screen was collected and weighed, and the undersize was placed on the next smaller screen. The process was then repeated until all four manual screens had been used.

The undersize from the 2.54 cm manually held screen was next processed through the SWECO screens. The screening time was standardized at fifteen minutes.

Size distribution curves for each sample of shredded material were plotted from the data acquired from the screening operation. From the curves, characteristic size (63.2 percent cumulation passing by weight) and nominal size (90 percent cumulation passing) were determined and recorded.

DEGREE OF SIZE REDUCTION

The degree of size reduction (Z_o) is a dimensionless term defined as

$$Z_o = \frac{F_o - X_o}{F_o} \qquad (1)$$

where F_o is the feed size and X_o is the product size expressed in centimeters or inches.

Values of Z_o range from zero (no size reduction) to a maximum of 1.0, which corresponds to an infinitely small product size.

POWER DRAW

Power draw during freewheeling operation and the test intervals was determined from the recorder charts. Power (P) was calculated using the transducer constant (K_e), the product ($R_V R_C$) of the current and potential transformer ratios, the chart speed (v), and the recorded pulse rate (R_p). The calculation of power is based on the relation,

$$P = Cv\ R_V R_C\ K_e\ R_p \tag{2}$$

where C is a constant that preserves the dimensionality of the equation.

THROUGHPUT AND HOLDUP MEASUREMENTS

Measurements of throughput were made by removing and weighing shredded material from a measured length of conveyor belt. The calculation of throughput was made using the following relation,

$$\dot{m} = 3.6\ \frac{MV}{L} \tag{3}$$

where: $\dot{m}$ = mass flow rate (Mg/h)

M = mass of the total sample removed from the discharge conveyor (kg)

L = length of the conveyor segment from which the throughput sample was collected (m)

V = speed of the conveyor from which the flow rate sample was collected (m/sec)

Holdup was determined by weighing the material that accumulated beneath the shredder after both the feed and discharge conveyors had been stopped. To determine true holdup (H*), a correction had to be applied to the measured holdup (H) in order to account for material that resided on the discharge conveyor at the moment it was stopped. Consequently, the true or corrected holdup is represented by the equation,

$$H^* = H - 0.28\ \frac{\dot{m}}{V}\ L^* \tag{4}$$

where: H = measured holdup (kg)

L* = length of the conveyor belt beneath the shredder discharge (m)

$\dot{m}$ = mass throughput (Mg/h)

V = belt speed (m/s)

This equation assumes that at the instant the conveyors are stopped, the section of conveyor under the shredder outlet is already full to the bed depth of the outfeed conveyor. While this may be unlikely, the equation is considered to be the best available for determining true hold-up.

SPECIFIC ENERGY

Specific energy requirements were determined using the following relation,

$$E = (P_G - P_{FW})/\dot{m} \qquad (5)$$

where: E = specific energy (kWh/Mg)

P = gross power requirement (kW)

P_{FW} = freewheeling power requirement (kW)

$\dot{m}$ = mass throughput (Mg/h)

Specific energy expressed on an air-dry weight basis (E_o) is calculated using a mass flow rate expressed on the same basis ($\dot{m}_d$).

SECTION 5

EXPERIMENTAL PROCEDURES

GENERAL PROCEDURES

Installation of the potential and current transformers was done at each site by qualified electricians and connected to the power monitoring equipment under the direction of Cal Recovery personnel. After installation, the system was tested to insure that all the electrical connections were correct and that the equipment had sustained no damage during shipment. On actual days of testing, the monitoring equipment was turned on and allowed to warm up for at least half an hour before data were collected. Several times during each day of testing, freewheeling power measurements were taken, including one which was obtained shortly after shredder startup with the rest obtained as shredding operations permitted throughout the day. Freewheeling power is defined as the power required to maintain constant rotational velocity of the shredder rotor under a no-load condition (i.e., during idling).

Flow rate samples and power level data were collected under a number of different operating conditions for the purpose of characterizing the shredders. To guarantee that the flow rate sample coincided exactly with the interval during which the power was monitored, it was necessary to accurately determine both the distance from the center line of the shredder discharge to the center line of the segment of the discharge conveyor from which the flow rate sample was gathered and the speed of the discharge conveyor itself. With the shredder sampling distance and conveyor speed known, it was generally possible to calculate the elapsed time needed for the sample to travel from the shredder to the point of sample collection from

$$t = \frac{d_1}{V} + \left(\frac{2h}{g}\right)^{1/2} \qquad (6)$$

where: t = elapsed time (sec)

d_1 = shredder center line to sample center line distance (m)

V = speed of the conveyor from which the flow rate sample was collected (m/sec)

h = distance from the bottom of the grates at the center line of the shredder to the top of the discharge conveyor

g = acceleration due to gravity (m/sec^2)

The term $(2h/g)^{1/2}$ in Equation 6 represents the the time required for shredded material to drop from the grates of the shredder to the discharge conveyor belt.

When the actual power-flow rate test was being done, the time at which the discharge conveyor stopped was marked on the chart and a value for the elapsed time was calculated. The point on the chart recording of the power level corresponding to the time during which the flow rate sample was just emerging from the shredder was found by measuring the distance, d, from the mark identifying the point where the discharge conveyor was stopped. A value for d was found from

$$d = v\ t \tag{7}$$

where: d = distance from discharge conveyor stop mark on the chart recording to the center of the chart interval during which the flow rate sample was emerging from the shredder (m)

v = chart recorder speed (m/sec)

t = elapsed time (sec)

The complete interval on the chart recording during which the flow rate sample was being discharged was identified by measuring the distance $\pm \Delta$ from the point marking the center of the sample interval. A value for Δ is obtained from

$$\Delta = \frac{1}{2}\ \frac{L}{V}\ v \tag{8}$$

where: L = length of the conveyor segment from which the flow rate sample was collected (m)

V = speed of the conveyor from which the flow rate sample was collected (m/sec)

v = chart recorder speed (m/sec)

Preparation of the refuse samples for shipment included bagging and weighing the samples. The bagged samples were tagged with the date, weight, and sample number, placed in a second plastic bag to insure against puncture damage to the inner bag, and packed into shipping containers for transport to the laboratory for size and moisture analysis.

In order to ensure that a representative sample for the size distribution analysis was obtained, the sample size was varied according to the grate spacing of the shredder undergoing testing. Grate spacing is defined as that dimension of the grate opening that is tangential to the circular path of the rotating hammers. In general, the larger the grate spacing, the larger the sample that needed to be gathered. The reason for the selection of this method for determination of sample size follows from the fact that, in general, relatively large particles issue from grates with large openings. Consequently in order to assure a sufficient number of particles for

determination of the particle size spectrum, a large particle size dictates a large sample size. Estimation of the sample size was made from Table 6.

The actual sample used for the size distribution and moisture analysis was obtained by thoroughly mixing the flow rate sample and dividing it into equal portions of the correct size. One of the portions so obtained was then prepared and shipped for subsequent size distribution and moisture analysis.

TABLE 6. SAMPLE SIZE

Grate Spacing		Sample Size	
cm	(inches)	kg	(pounds)
20	(7.9)	10	(22.1)
15	(5.9)	7.5	(16.5)
10	(3.9)	5	(11.0)
5	(2.0)	2.5	(5.5)

APPLETON PROCEDURE

Since both shredders at Appleton use the same discharge conveyor, for purposes of the present test program only the West mill was fed refuse during the tests. In addition, the water spray used to control dust inside the shredders was turned off several minutes before all of the tests.

The motor control room in Appleton is located directly underneath the main control room. The person monitoring the power requirement of the shredder under test stood at the entrance to the motor control room in sight of the monitoring equipment. An operator was in the main control room, while another member of the testing team was stationed at the end of the horizontal discharge conveyor. After recording an interval of relatively constant power, the person monitoring the power signaled both visually and audibly to the operator in the control room and marked the time of the signal on the chart recording. Upon receiving the signal, the control room operator stopped both the feed and discharge conveyors and allowed the shredder to empty. While the shredder was emptying, the final five meters of refuse on the discharge conveyor was collected and weighed in order to obtain flow rate data. Correlation of the flow rate and power data was accomplished through utilization of the methods outlined under General Procedures.

After collecting the flow rate sample, the discharge conveyor was advanced so the shredder holdup (the mass of material actually within the shredder at the instant the feed conveyor was stopped) could also be collected and weighed.

ODESSA PROCEDURE

The flow rate sampling point was selected to be a 2 m section of conveyor belt 15 m downstream of the shredder discharge. The belt speed and distance from the centerline of the sampling area to the centerline of the shredder were measured and used in conjunction with Equation 6 to obtain a value for the time, t, needed for refuse to travel from the shredder to the midpoint of the sampling area.

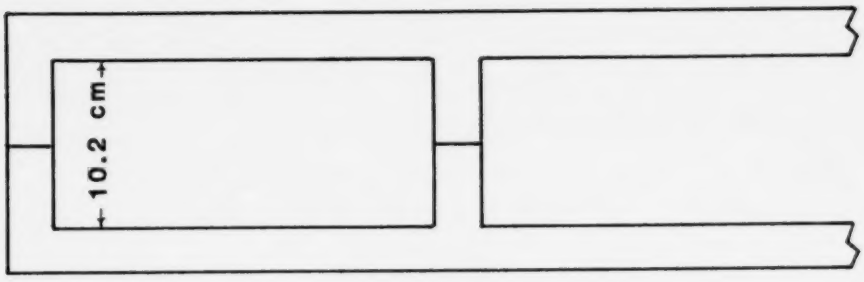
The power monitoring equipment was placed in the motor control room (located under the feed conveyor and just behind the shredder discharge). Due to the potential danger of falling objects and explosions, personnel were not permitted in the shredder pit while refuse was being fed to the shredder, thus limiting the opportunities for sampling to those times when a full transfer trailer was being replaced by an empty one. At the commencement of a test interval, the chart recorder was started as the full transfer trailer was being removed. The hydraulic push pit into which shredded refuse was discharged had enough capacity to hold roughly the amount of refuse which could be shredded in five minutes of normal operation. The feed conveyor was restarted and refuse fed to the shredder until the shredder motor current monitor in the control room indicated a relatively constant load at which time a signal was given to the shredder operator to stop the feed and discharge conveyors. The feed rate sample and holdup were collected and weighed subsequently.

RICHMOND PROCEDURE

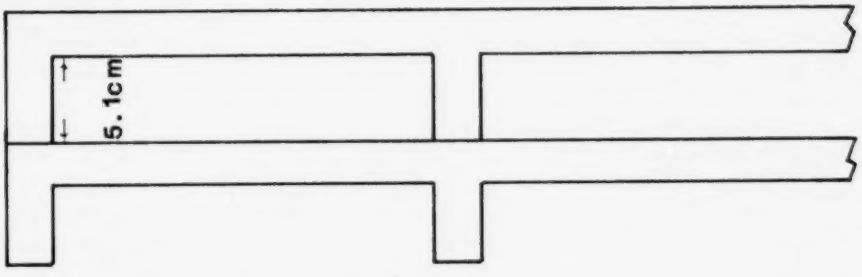
For each test, shredded material was collected from the shredder discharge conveyor for the purpose of determining throughput values and particle size distribution. The sampling point was approximately 2 m downstream from the centerline of the hammermill. In addition to the collection of the throughput samples and subsamples for subsequent particle size analysis, mill holdup was collected from beneath the shredder and weighed at the conclusion of each throughput test.

The Richmond test series consisted of four separate sub-tests conducted in two phases. Each phase simulated a two-stage size reduction line. Phase I consisted of primary size reduction using a 10.2 cm (4.0 in.) grate spacing and secondary size reduction using a grate spacing of 5.1 cm (2.0 in.). The 10.2 cm grate spacing was obtained by using the same grate bars used to set the 5.1 cm spacing. However, the bars were arranged such that the openings of adjacent bars faced one another, as shown in Figure 9. Thus, the size of the opening was doubled (i.e., from 5.1 to 10.2 cm). Inasmuch as the same grate bars were used (i.e., geometry and number) the open area percentage is identical for both grate arrangements. Processing for the Phase I tests consisted of size reduction of raw MSW through the mill equipped with a 10.2 cm grate spacing followed by a grate change and a re-shredding of the mixed primary product through the mill equipped with a grate spacing of 5.1 cm.

The Phase II tests involved simulating a flail mill for primary size reduction and the use of a 5.1 cm grate spacing for the secondary size



10.2 cm spacing



5.1 cm spacing

Figure 9. Grate arrangement used in the Richmond tests.

reduction. For the purpose of simulating a flail mill, the primary size reduction step was accomplished by operating the hammermill without any grates. Without grate bars, the mill produces a coarse product which consists primarily of the intact contents of plastic and kraft bags discarded in the raw waste. Subsequent to flail mill shredding of the raw MSW, grates were installed in the mill such that the grate spacing was 5.1 cm. The mixed product from the flail mill was then subjected to secondary size reduction.

A summary of the operating parameters for the Richmond tests is presented in Table 7.

TABLE 7. OPERATING PARAMETERS FOR THE MULTIPLE-STAGE TEST PROGRAM AT THE RICHMOND FACILITY

Phase	Test No.	Grate Opening (cm)	Feed Material
I	1	10.2	Raw MSW
	2	5.1	Material shredded in Test No. 1
II	3	No grates	Raw MSW
	4	5.1	Material shredded in Test No. 3

Measurements of energy consumption, throughput and holdup were made during the course of both phases (i.e., I and II), and subsamples were collected for particle size analyses.

SECTION 6

RESULTS AND DISCUSSION

PERFORMANCE DATA

Performance data for the tests conducted at the Richmond, Appleton West, and Odessa facilities are presented in Appendices A, B, and C. The data include: throughputs (wet and air-dry bases); feedstock moisture contents; holdup; power requirements (gross, freewheeling and net); specific energy (wet and air-dry bases); product particle size (characteristic and nominal); and degree of size reduction. Table 8 shows the range of values for key parameters and variables. It is to be noted that the general range of data covers a wide spectrum of shredder operating conditions.

OPTIMIZING DESIGN AND OPERATING VARIABLES

Prior to the present study, procedures for the determination of the optimum design and operating variables for minimizing energy usage in a size reduction facility had not been formulated. Although single- and two-stage shredding of raw MSW have been practiced for approximately ten years, the relative efficiency of one method over the other is controversial. Only limited information has been available for comparing efficiencies since conducting tests at a commercial plant is usually not possible due to the interruptions in normal plant operation which occur as a result of the required changes to grate spacing.

An earlier study by Savage and Trezek [2] examined the relative merits of single- and two-stage size reduction of raw MSW. An analytical approach based on functional relationships between specific energy (E_o), degree of size reduction (Z_o), and grate spacing (D_o) was used to develop Figure 10. This figure, which allows prediction and evaluation of shredder performance without resorting to actual testing, was used to assess the relative merits of single- and two-stage size reduction of raw MSW. It was concluded from the study that two-stage size reduction was considerably more energy efficient than single-stage size reduction.

In contrast to the findings of Savage and Trezek, Savage and Shiflett [1] using different data found that single-stage size reduction was more efficient than two-stage size reduction in terms of specific energy requirements. In their study, a comparison of specific energy requirements was presented for the Ames two-stage shredding line and the Baltimore County single-stage shredding operation.

TABLE 8. SHREDDER PERFORMANCE DATA RANGE

Test	N_H	MC (%)	$\dot{m}_w$ (Mg/h)	$\dot{m}_d$ (Mg/h)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg)	E_o (kWh/Mg)	X_o (cm)
Appleton West	24-64	15-37	2-58	1-44	7-534	43-350	35	8-316	2-10	2-13	0.7-4.4
Odessa	10-14	13-37	11-191	9-139	16-915	61-671	47-57	13-623	1-17	1-20	1.0-9.0
Richmond	44	12-30	0.2-13	0.2-10	0.2-70	4-200	24-30	1-175	0.4-23	0.5-28	0.6-11.5
General Range	10-64	12-37	0.2-191	0.2-139	0.2-915	4-671	24-57	1-623	1-23	0.5-28	0.7-11.5

N_H = number of hammers

MC = moisture content

$\dot{m}_w$ = throughput (wet basis)

$\dot{m}_d$ = throughput (air-dry basis)

MC = moisture content

H* = corrected holdup

P_G = gross power

P_{FW} = freewheeling power

P_N = net power

E_{o_w} = specific energy (wet basis)

E_o = specific energy (air-dry basis)

X_o = characteristic product size

X_o = characteristic product size

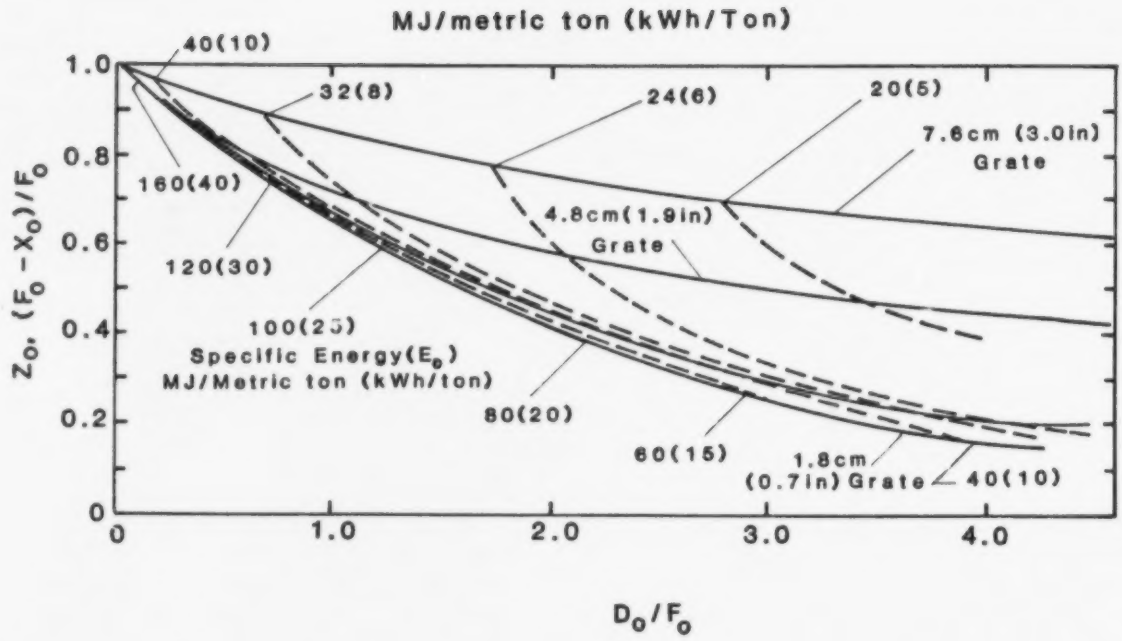


Figure 10. Degree of size reduction and specific energy requirement for shredding raw MSW as a function of D_o/F_o [2].

To provide more data for the development of specific and generalized procedures for the comparative analysis and optimization of energy requirements for multiple- and single-stage shredding, a test program at the Richmond Field Station was devised. The program involved gathering and analyzing data from four interrelated shredding tests and the subsequent development of procedures for comparing single- and multiple-stage shredding scenarios. Details of the test procedures are presented in Section 5. The following summarizes the basic features of each test.

Test 1 - Raw refuse (having a nominal average characteristic size of 14 cm) was shredded in the Richmond hammermill fitted with a grate having 10.2 cm wide spacings.

Test 2 - The product from Test 1 was mixed and re-shredded in the mill fitted with a grate having 5.1 cm wide spacings.

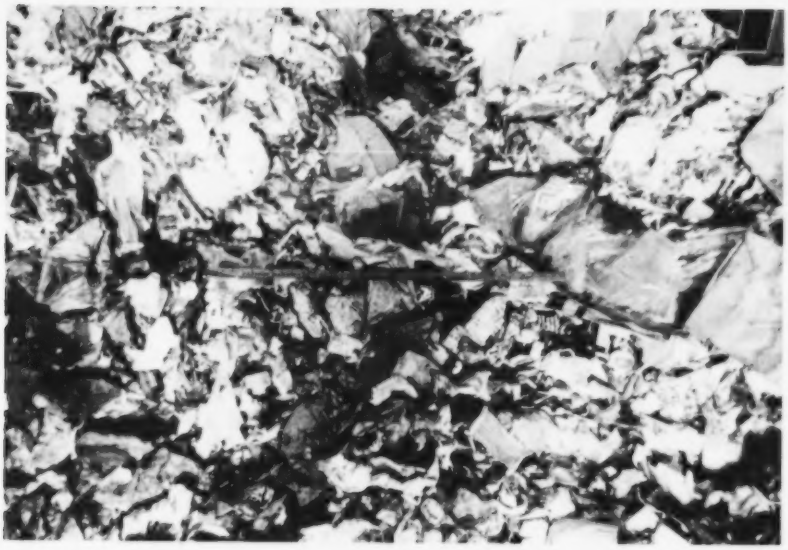
Test 3 - Raw refuse was shredded in the Richmond mill in the absence of a grate (i.e., the refuse was "flail milled").

Test 4 - The product from Test 3 was shredded in the Richmond mill fitted with a grate having 5.1 cm wide spacings.

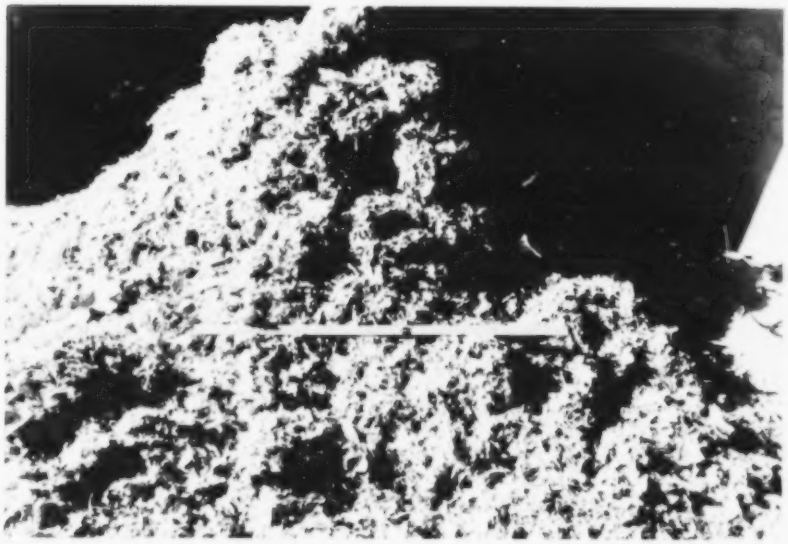
Data collected from these tests are given in Appendix A. The relatively more coarse and heterogeneous product from the flail mill is compared to the product from secondary size reduction in Figure 11.

Several new procedures for the comparative analysis and optimization of single- and multiple-stage shredding are described in the following pages. These procedures were developed in response to the observation that relatively high correlation coefficients existed for the data relating net specific energy (E_0) as a function of product size (X_0) and degree of size reduction (Z_0), and product size as a function of throughput ($\dot{m}_d$). The first procedure (Procedure I) utilizes an approach which is site specific, i.e., test results are derived for a particular shredder (in this instance the Richmond hammermill) and operating conditions. The second and third procedures (Procedures II and III) generalize the site specific data by relating data to the dimensionless parameter "degree of size reduction." Procedure II uses product size as the key parameter relating degree of size reduction to specific energy requirements. Procedure III is similar to Procedure II except that grate spacing is used as the key parameter. The final procedure (Procedure IV) is similar to Procedure II except that it is based on a large array of data collected from six different hammermills. Selection of an energy efficient system involves comparing gross specific energies calculated from the sum of net and freewheeling specific energies of the component shredders. The freewheeling specific energy can be calculated by dividing the freewheeling power requirements (P_{FW}) by the average throughput ($\bar{\dot{m}}_d$).

A number of shredding scenarios have been devised to test the flexibility of each procedure and to provide data for comparative analysis. In all cases, specific energy and throughput are expressed on an air-dry weight basis.



Character of the product material after flail milling (no grate bars).



Character of the product material after secondary size reduction.

Figure 11. Product size after flail milling and after secondary milling (meter stick is shown in photos for size reference).

Procedure I

It was found that for each of the Richmond tests, E_o could be expressed as a linear function of X_o, and similarly X_o could be expressed as a linear function of $\dot{m}_d$ (Figures 12 and 13). Using the derived equations, it is then possible to graphically describe specific energy and particle size as a function of $\dot{m}_d$ as shown in Figures 14 and 15, and to use these plots as a means of determining total specific energy for a range of single-stage and two-stage scenarios.

Figure 13 shows product size decreasing as the throughput is increased. The effect is particularly noticeable for data in the area of low throughput (i.e., 0 to 2 Mg/h) where the material within the shredder may be envisioned to be a dilute mixture. As the throughput is increased, the amount of material within the shredder increases dramatically. Thus, there is an increase in the mill holdup and the residence time of material within the shredder. The longer residence time results in the refuse being exposed to more hammer impacts than at dilute loadings. Consequently, a finer size material is produced. Further discussion of mill holdup and throughput is given in the Section "Throughput/Mill Holdup Relation," presented later in this chapter.

Example --

Calculate the total specific energy requirement (net) for two-stage shredding of MSW using the Richmond mill as a flail mill and then as a mill with a 5.1 cm grate spacing to reduce the flail mill product. The average feedstock and final product sizes are 14 cm and 0.85 cm, respectively, and the throughput ($\dot{m}_d$) is 3.5 Mg/h.

From Figure 15:

E_o = 1 kWh/Mg for flail mill reduction ($\dot{m}_d$ = 3.5 Mg/h)

and

E_o = 22 kWh/Mg for X_o = 0.85 cm ($\dot{m}_d$ = 6.1 Mg/h)

Total E_o = 1 + 22

= 23 kWh/Mg

Note that this procedure implies secondary size reduction of an intermediate size product (X_o = 8.75 cm) at a throughput of 6.1 Mg/h which is almost twice the stipulated throughput. By using a throughput of 3.5 Mg/h, the size of the final product would be approximately 1.2 cm and total E_o would be 19 kWh/Mg. The ability of the two-stage system to generate a 0.85 cm product is therefore dependent on storage of the flail mill product and subsequent operation of the secondary shredder at 6 Mg/h.

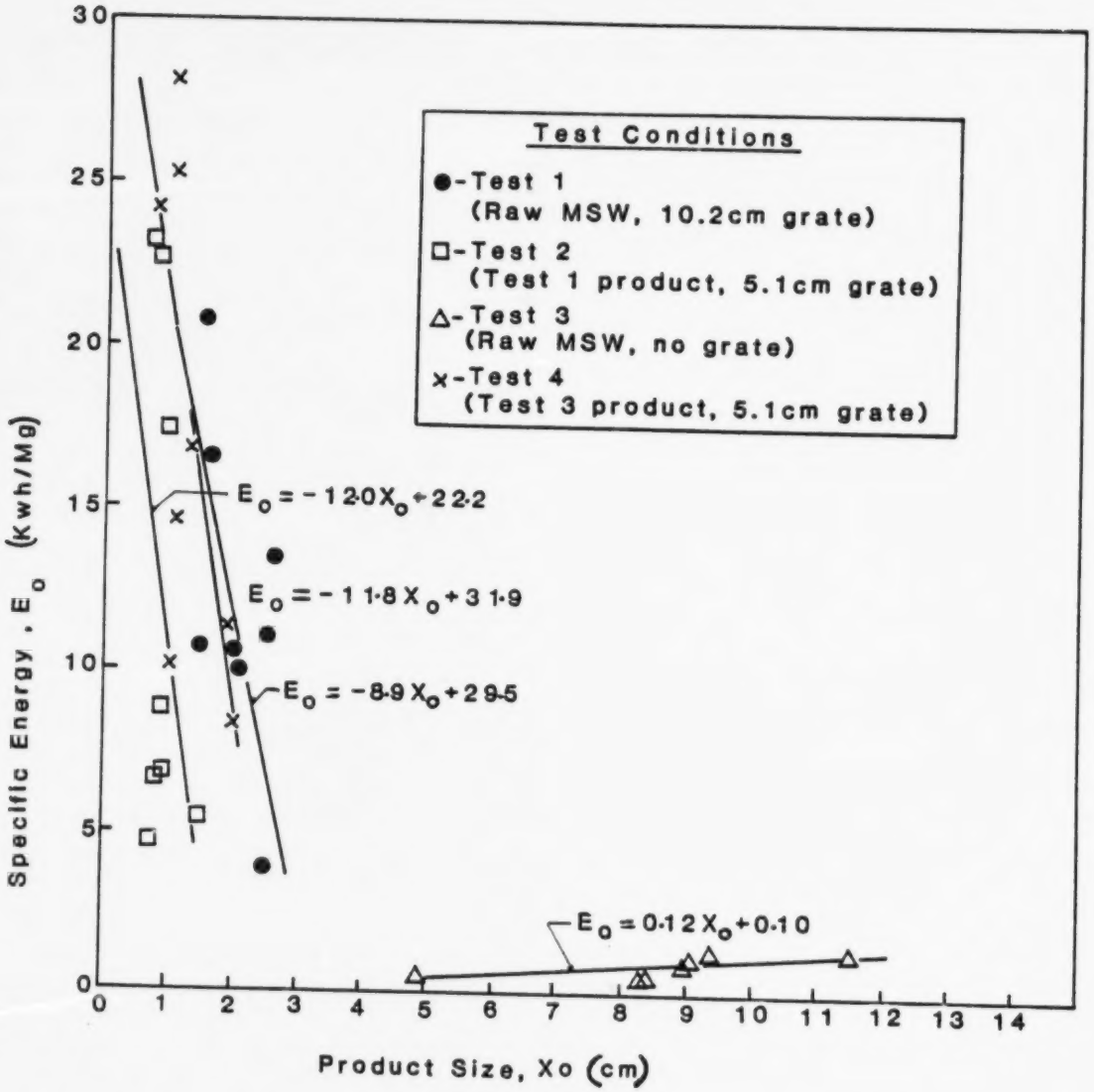


Figure 12. Specific energy as a function of product size and test conditions (Richmond, October 1981; Tests 1, 2, 3, and 4).

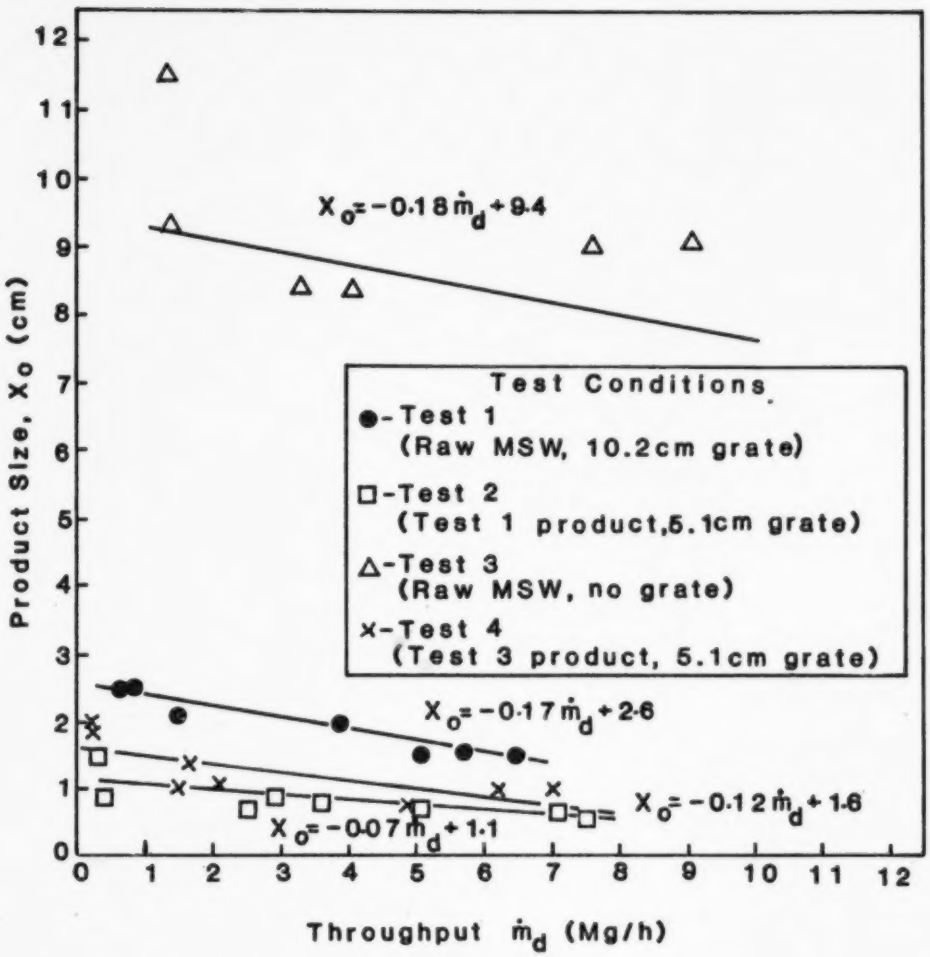


Figure 13. Product size as a function of throughput and test conditions (Richmond, October 1981; Tests 1, 2, 3, and 4).

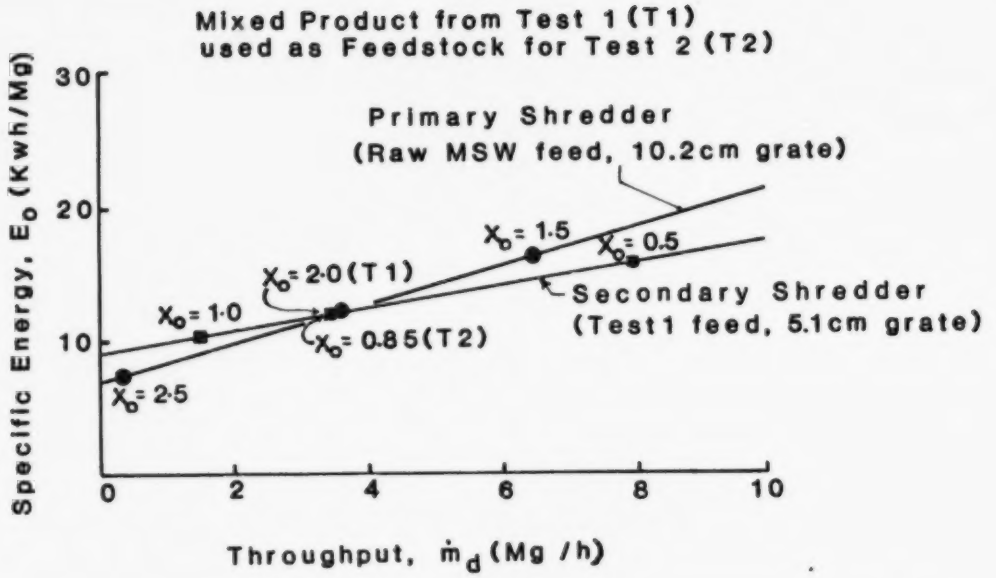


Figure 14. Relation between specific energy, average throughput, and product size for site specific two-stage size reduction (Richmond, October 1981; Tests 1 and 2).

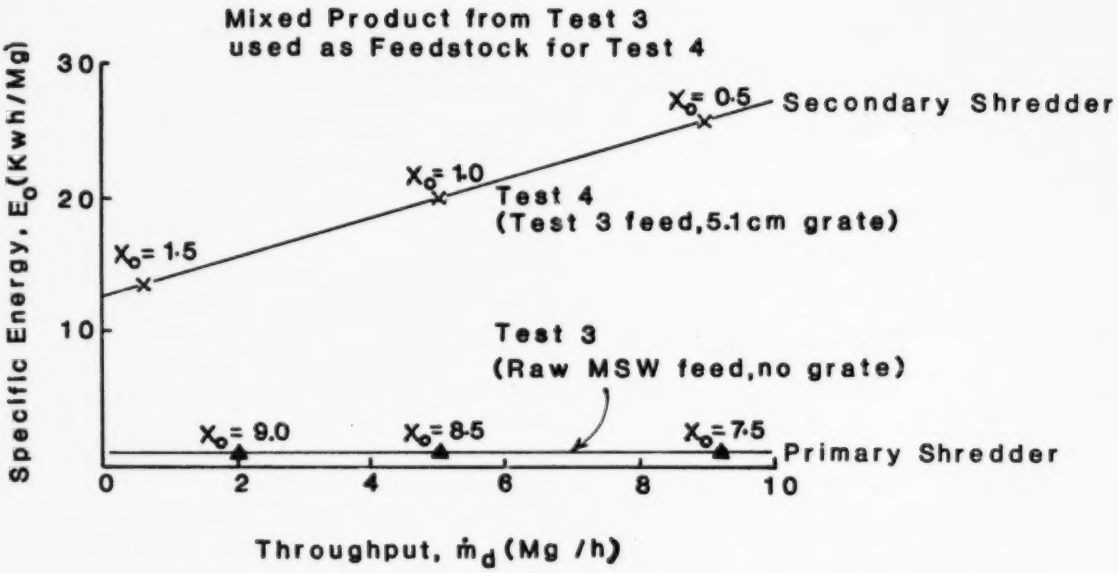


Figure 15. Relation between specific energy, average throughput, and product size for site specific two-stage size reduction (Richmond, October 1981; Tests 3 and 4).

It should be noted that the validity of the above procedure is dependent on the assumption that the intermediate product size (ranging between 7.5 and 9.5 cm) does not significantly influence the specific energy requirement of the secondary shredding or the product size.

Procedure II

This procedure utilizes Figure 16, which shows specific energy as a function of degree of size reduction (Z_o) and characteristic product size (X_o) for the Richmond test data. Average throughputs are shown for four ranges of E_o.

Example--

Calculate the total specific energy required for single- and two-stage shredding of MSW to a product size of 0.85 cm. Assume the feed size of MSW (F_o) is 14 cm and the intermediate particle size (X_o) is 2.0 cm.

Single-stage

$$Z_o = (F_o - X_o)/F_o$$
$$= (14 - 0.85)/14$$
$$= 0.94$$

and from Figure 16

E_o = 43 kWh/Mg for X_o = 0.85 cm

Two-stage

For primary size reduction to X_o = 2.0 cm

$$Z_o = (F_o - X_o)/F_o$$
$$= (14 - 2.0)/14$$
$$= 0.86$$

and from Figure 16

E_o = 11 kWh/Mg

For secondary size reduction to X_o = 0.85 cm

$$Z_o = (F_o - X_o)/F_o$$
$$= (2.0 - 0.85)/2.0$$
$$= 0.58$$

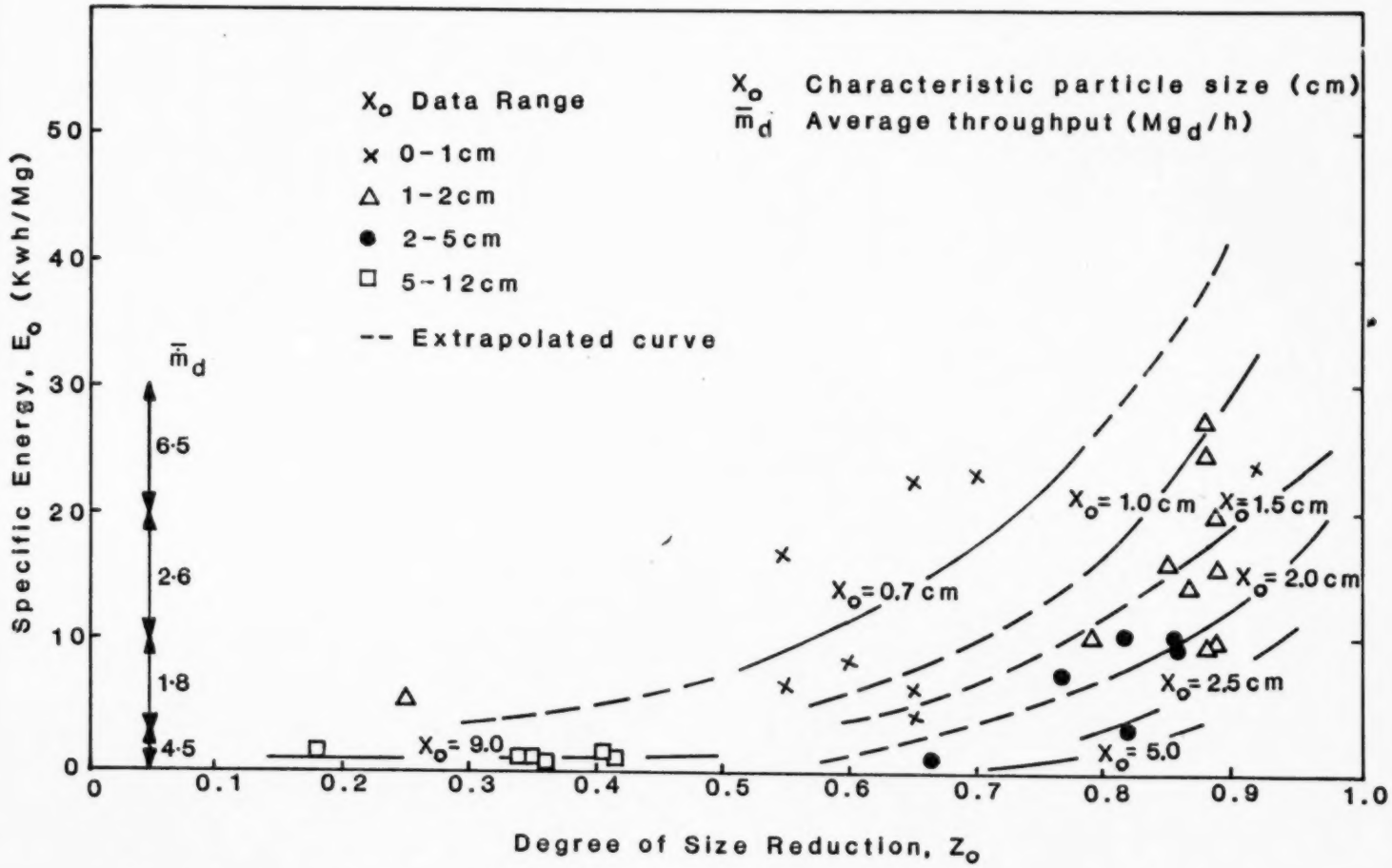


Figure 16. Specific energy as a function of degree of size reduction and characteristic particle size (Richmond, October 1981 test).

and from Figure 16

$E_o = 8$ kWh/Mg_d

Total specific energy equals the sum of primary and secondary specific energies.

Therefore, total $E_o = 11 + 8$

$= 19$ kWh/Mg

It should be noted that while this procedure is more generally applicable than Procedure I due to the use of Z_o instead of product size X_o, it is encumbered with greater uncertainty. Unfortunately, some of the curves are formed from a limited number of highly variable data encompassing only a small range of Z_o values. The use of this plot may result in significant error, particularly if E_o values are extracted from the extrapolated curve sections.

Procedure III

The third procedure involves the use of Figure 17, a similar plot to that of Procedure II except that the grate spacing rather than product size is used as the key variable.

Example--

Calculate the total specific energy required for two-stage shredding of MSW using two hammermills fitted with grates having 10.2 cm and 5.1 cm grate spacings. The feed size (F_o) is 14 cm and the final product size is 1.2 cm.

For primary shredding to an intermediate size of $X_o = 2.0$ cm

$Z_o = (F_o - X_o)/F_o$

$= (14.0 - 2.0)/14$

$= 0.86$

and from Figure 17

$E_o = 15$ kWh/Mg

For secondary shredding

$Z_o = (F_o - X_o)/F_o$

$= (2.0 - 1.2)/2.0$

$= 0.40$

and from Figure 17

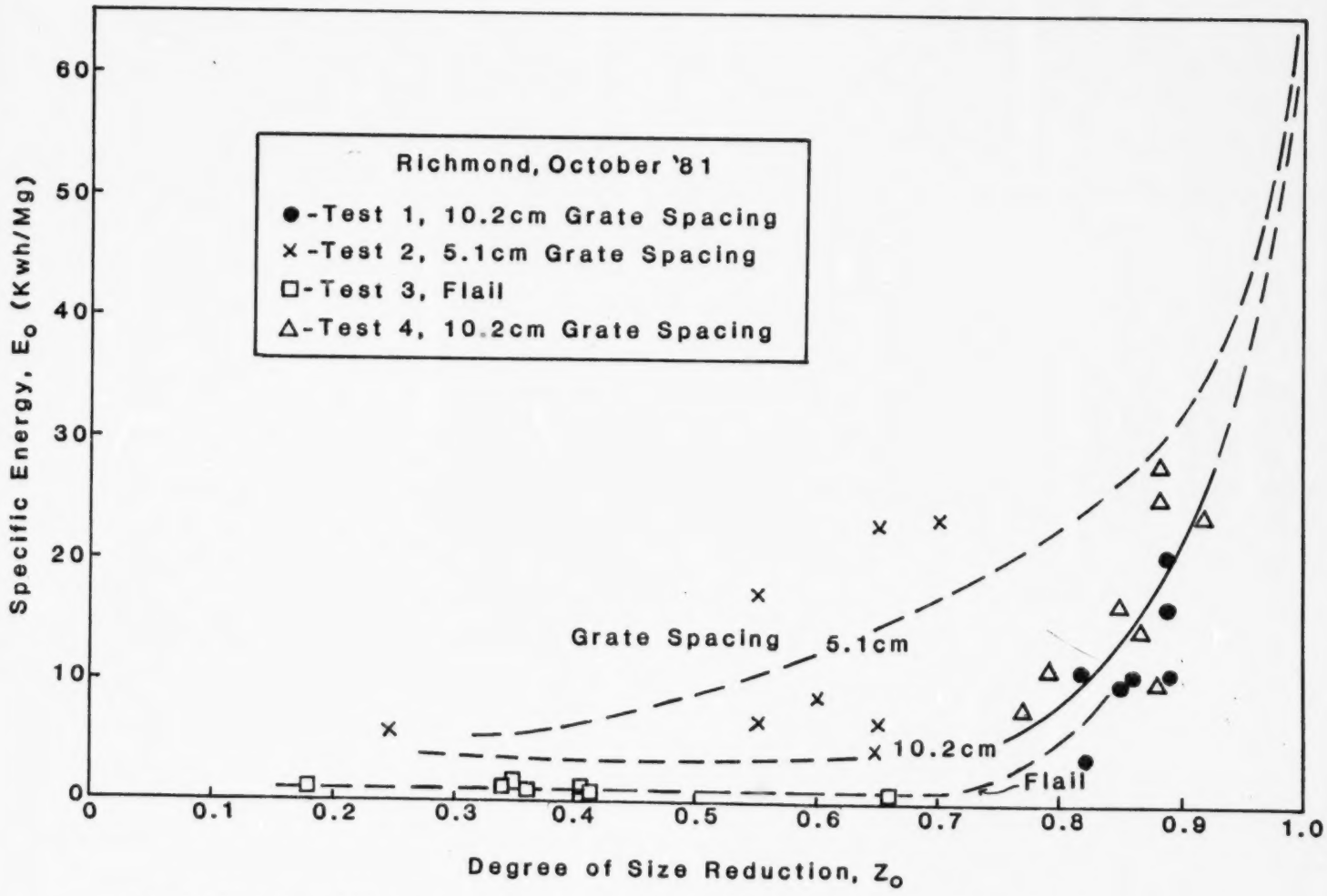


Figure 17. Specific energy as a function of degree of size reduction and grate spacing (Richmond, October 1981 test).

and from Figure 17

E_o = 6 kWh/Mg

Total specific energy equals the sum of primary and secondary specific energies.

Therefore, total E_o = 15 + 6

= 21 kWh/Mg

It should be noted that this procedure is subject to the same reservations expressed for Procedure II, i.e., the curves are derived from highly variable data which in some cases spans a relatively small Z_o range. The use of this plot may result in significant error, particulary if E_o values are extracted from the extrapolated curve sections.

Comparative Analysis of Procedures I, II, and III

Total specific energy values for a matrix of single- and multiple-stage design and operating variables were calculated using each of the previously described procedures. These specific energy values are derived from data obtained in the Richmond test program. A summary of the results is presented in Table 9.

Since Procedure I is inherently more accurate than Procedures II and III, it can be used as a reference for evaluating the effectiveness of Procedures II and III. From an analysis of the data in Table 9, it is concluded that:

1) Based on Procedure I data, there appears to be no significant difference in the specific energy requirements for single- versus multiple-stage size reduction. This is in contrast to data from Procedures II and III which indicate that a significant reduction in specific energy requirement may be possible using two-stage shredding if grate size and mill sequence are optimized.

2) Procedures II and III indicate that the use of a flail mill followed by a secondary shredder with a 10.2 cm grate spacing will result in optimum minimum specific energy requirement for a reduction in size from 14 to 2 cm. The data is inconclusive for larger degrees of size reduction.

3) Additional test data are required to improve the precision of the curves used in Procedures II and III.

Procedure IV

As a result of the need to improve precision, the plot shown in Figure 18 was developed using available laboratory and field data. This includes data from tests conducted at Richmond in October 81 (Appendix A) and August

TABLE 9. SUMMARY OF SPECIFIC ENERGY REQUIREMENTS (kWh/Mg) FOR SINGLE- AND MULTIPLE-STAGE SIZE REDUCTION OF MSW[1]

Range of Size Reduction[3]	Procedure I						Procedure II						Procedure III					
	-- Grate Size and Mill Sequence[2] --						--- Grate Size and Mill Sequence ---						--- Grate Size and Mill Sequence ---					
	5.1	10.2	FM/ 5.1	10.2/ 5.1	5.1/ 5.1	FM/ 10.2	5.1	10.2	FM/ 5.1	10.2/ 5.1	5.1/ 5.1	FM/ 10.2	5.1	10.2	FM/ 5.1	10.2/ 5.1	5.1/ 5.1	FM/ 10.2
14 cm → 0.85 cm	NA[4]	NA	23	24	NA	NA	43	43	38	19	29	38	40	33	33	29	40	26
14 cm → 1.2 cm	18	19	19	21	NA	NA	27	27	23	14	NA	22	20	34	29	20	NA	16
14 cm → 2.0 cm	NA	12	NA	NA	NA	NA	11	11	8	NA	NA	8	28	14	23	NA	NA	7

1. Based on test data collected at the Richmond Field Station.

2. Grate spacing and sequence legend:

   5.1 = 5.1 cm grate spacing (single-stage)
   10.2 = 10.2 cm grate spacing (single-stage)
   FM/5.1 = flail/5.1 cm grate spacing (two-stage)
   10.2/5.1 = 10.2cm/5.1 cm grate spacings (two-stage)
   5.1/5.1 = 5.1cm/5.1 cm grate spacings (two-stage)
   FM/10.2 = flail/10.2 cm grate spacing (two-stage)

3. Assumed intermediate product size (X_o).

   FM/5.1 X_o = 9.0 cm
   10.2/5.1 X_o = 2.0 cm
   5.1/5.1 X_o = 1.2 cm
   FM/10.2 X_o = 9.0 cm

4. NA = Not applicable to analysis.

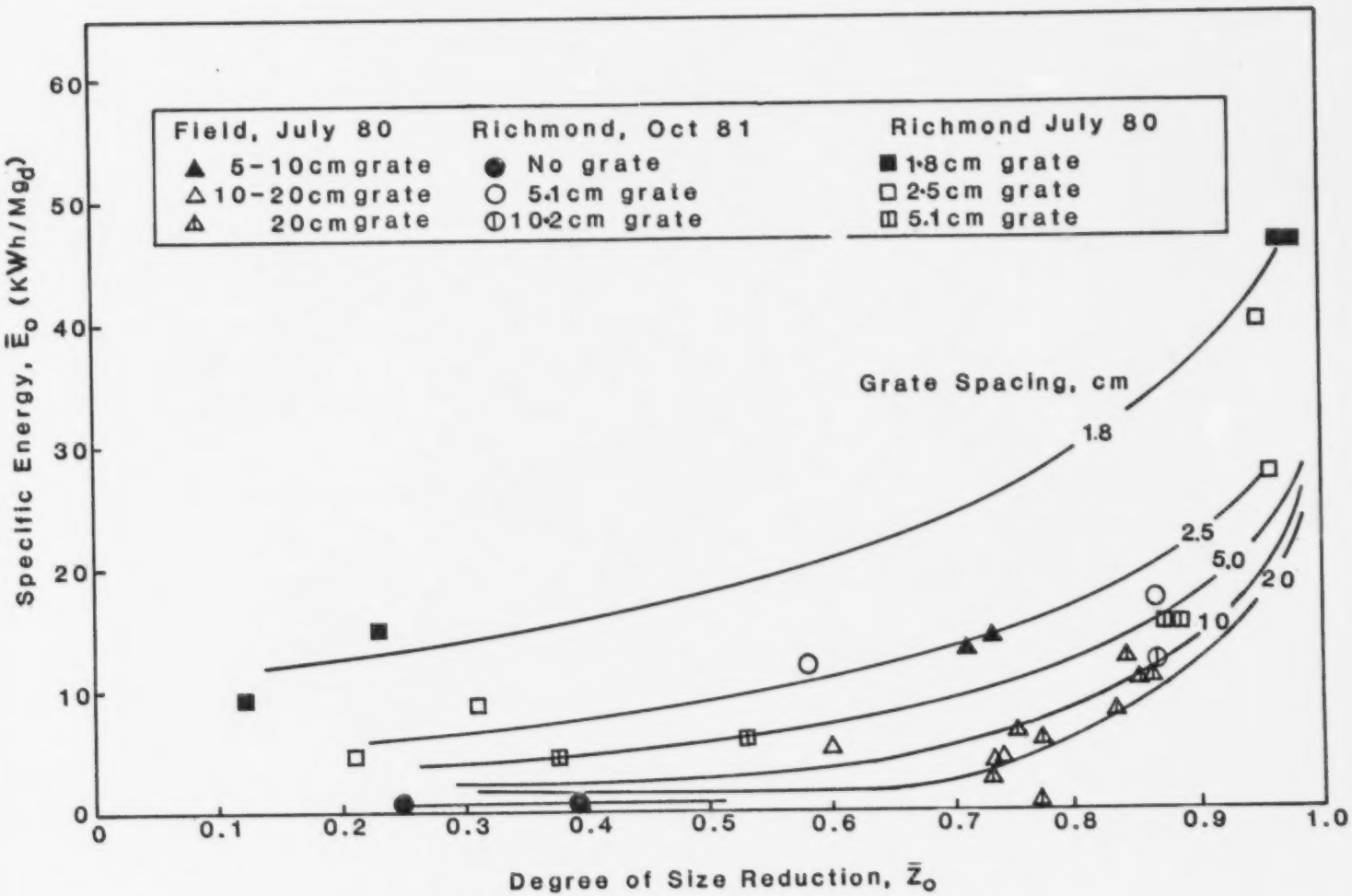


Figure 18. Specific energy as a function of degree of size reduction (Richmond and field data for MSW).

80 [2], at Appleton West (Appendix B), at Odessa (Appendix C), and at various commercial facilities [1]. $\overline{E}_o$ and $\overline{Z}_o$ are averages of the data available from each test run in contrast to values presented in Figure 17 which are the discrete data from four test runs. As a consequence, the curves in Figure 18 are dissimilar to those shown in Figure 17. However, it is expected that the use of Figure 18 will improve the precision of specific energy estimates since the curves were formed from a large array of data collected from six different hammermills.

Example--

Calculate the total specific energy for two-stage shredding g MSW using two hammermills fitted with grates having 10.2 cm and 5.1 cm grate spacing. The feed size (F_o) is 14 cm and the intermediate and final product sizes are 2.0 and 1.2 cm, respectively.

For primary shredding to an intermediate size of X_o = 2.0 cm

$$Z_o = (F_o - X_o)/F_o$$

$$= (14.0 - 2.0)/14.0$$

$$= 0.86$$

and from Figure 18

$$E_o = 14 \text{ kWh/Mg}_d$$

For secondary shredding

$$Z_o = (F_o - X_o)/F_o$$

$$= (2.0 - 1.2)/2.0$$

$$= 0.40$$

and from Figure 18

$$E_o = 6 \text{ kWh/Mg}_d$$

Total specific energy equals the sum of primary and secondary specific energies.

Therefore, total $E_o = 14 + 3$

$$= 17 \text{ kWh/Mg}_d$$

Table 10 shows the results of an analysis of single- and multiple-stage size reduction using Figure 18. The scenarios are the same as those previously evaluated and shown in Table 9. Comparison of E_o requirements

TABLE 10. SPECIFIC ENERGY REQUIREMENTS (kWh/Mg) FOR SINGLE- AND TWO-STAGE SIZE REDUCTION OF MSW - PROCEDURE IV[1]

Range of Size Reduction	Grate Size and Mill Sequence[2]						Predictive Equation[3]
	5.1	10.2	FM/5.1	10.2/5.1	5.1/5.1	FM/10.2	
14 cm → 0.85 cm	22[4,6] (27)[5,6]	18 (23)	19 (29)	20 (30)	23 (33)	16 (26)	20.7
14 cm → 1.2 cm	19 (24)	15 (20)	17 (27)	17 (27)	21 (31)	13 (23)	15.2
14 cm → 2.0 cm	15 (20)	12 (17)	13 (23)	14 (24)	17 (27)	9 (19)	9.6

1. Based on Figure 18.

2. Grate spacing and sequence legend:

   5.1 = 5.1 cm grate spacing (single-stage)
   10.2 = 10.2 cm grate spacing (single-stage)
   FM/5.1 = flail/5.1 cm grate spacing (two-stage)
   10.2/5.1 = 10.2cm/5.1 cm grate spacings (two-stage)
   5.1/5.1 = 5.1cm/5.1 cm grate spacings (two-stage)
   FM/10.2 = flail/10.2 cm grate spacing (two-stage)

3. $E_o = 17.91\ X_o^{-0.90}$; where: E_o = specific energy in kWh/Mg, and X_o = product size in cm.

4. Specific energy requirement (net), E_o.

5. Specific energy requirement (gross) = $E_o + P_{FW}/\dot{m}_d$

   Assumed freewheeling power (P_{FW}) = 25 kW per shredder

   and mass throughput ($\dot{m}_d$) = 5 Mg/h

6. Range of size reduction may not be obtainable in practice.

calculated using Procedure IV (Table 10) with E_0 requirements calculated using Procedures I, II, and III (Table 9) indicates that Procedure IV provides data which is relatively more accurate than that provided by Procedures II and III. This conclusion is based on the assumption that Procedure I is inherently more accurate than Procedures II, III, and IV.

Also shown in Table 10 for comparative purposes, are predicted values of average specific energy requirements for MSW size reduction based upon an equation developed as a result of previous work [1], and gross specific energy requirements (shown in parentheses) based on the inclusion of 5 kWh/Mg freewheeling energy requirement for each mill. The predictive equation results fall within the range of values calculated using the graphical procedures. The relatively wide range of values predicted by the equation and the graphical procedures are attributed to unaccounted operational and machine-specific variables.

The conclusions reached from the derived data presented in Table 10 are:

1. The lowest specific energy requirement (net) for producing a characteristic particle size (X_0) between 0.85 and 2.0 cm is obtained using a flail mill as the primary shredder in combination with a secondary shredder having a grate spacing selected by consideration of relations between grate spacing, throughput, and the desired particle size.

2. The most energy efficient system based on gross specific energy requirements is single-stage size reduction using a 10.2 cm grate spacing. However, for large degrees of size reduction (i.e., $X_0 \leq 1.2$ cm) either single-stage reduction with a 5.1 cm grate spacing or two-stage reduction using a flail mill and a shredder with a 10.2 cm grate spacing may be the most energy efficient and practical system.

3. For small degrees of size reduction (i.e., for $X_0 > 2.0$ cm), it is likely that single-stage shredding will be more efficient than two-stage.

It should be noted that the practicality of any system is dependent on the ability to generate the desired product size. Modification of machine parameters may be necessary to obtain large degrees of size reduction using single-stage size reduction. The modification of machine performance through manipulation of machine parameters is addressed in the following section.

MACHINE PARAMETERS AND SHREDDER PERFORMANCE

To our knowledge, published studies of refuse size reduction have not previously addressed machine parameters that govern the operational limitations of the equipment (i.e., maximum throughput, minimum product size, etc.) and the efficiency of size reduction as manifested in the percentage of mechanical energy that is converted into the breakage of material. Consequently, one of the purposes of this research was to study the internal structure of size reduction equipment in order to assess its influence on machine performance.

Machine Characteristics

Design data for a number of shredders were obtained from previous reports [1], from engineering drawings of shredders, and from actual measurements of shredder dimensions. Based upon the quality of the available data and judgments as to the parameters that would most likely play a prominent role in characterizing the effect of machine variables on shredder performance, a list of parameters were defined and calculated. They are presented in Table 11. The parameters were chosen primarily because they influence the comminution of the material and the flow of material through the shredder cavity. It should be noted that grate opening is defined as that dimension of the grate opening that is tangential to the circular path of the rotating hammers.

Volume was selected as a key parameter, since from the standpoint of designing a shredder cavity, it describes in a general manner the geometry of the cavity. The swept volume, open volume, closed volume, and total hammer volume were found to offer the greatest utility for analytical and design purposes. The swept volume was taken as being the cylindrical volume defined by the tip-to-tip diameter of the rotating hammers and the length of the shredder shaft within the shredding zone. The swept volume is composed of two quantities: 1) the closed volume (V_C) within the swept cylinder, i.e., the volume of the internal shredder hardware (e.g., rotor, rotor pins and disks, hammer, etc.); and 2) the open volume (V_O). The open volume is defined as the difference between the swept volume and the closed volume. The hammer volume (V_H) is the total volume of all hammers in the mill and is equal to the volume of one hammer multiplied by the total number of hammers. An additional prominent parameter is open volume fraction (V_{OF}), which is defined as open volume divided by swept volume.

From the data shown in Table 11, the reader may note that the percent variation in machine parameters varies from 29 percent for hammer tip speed to more than 2000 percent for grate opening.

Throughput/Mill Holdup Relation

Previous studies [1,2,3] have established the relation of throughput ($\dot{m}$) in Mg/h to mill holdup (H) in kg to be of the form,

$$\dot{m} = a_1 H^{b_1} \tag{9}$$

where a_1 and b_1 are numerical constants determined through standard curve fitting analysis. The present study confirmed that Equation 9 could be used to represent the throughput/holdup relation for a variety of hammermills and machine configurations. The relations are shown in Table 12. A significant finding is the fact that the exponent b_1 ranges from 0.5 to 1.5 for the hammermills studied. Prior research [1,2,3] on a Gruendler hammermill indicated values near unity.

TABLE 11. SHREDDER MACHINE PARAMETERS

Hammermill	Grate Opening, D_O (m)	Number of Hammers, N_H	Total Hammer Volume, V_H (m^3)	Hammer Tip Speed, S (m/s)	Open Volume, V_o (m^3)	Open Volume Fraction, V_{OF}	Closed Volume, V_C (m^3)	Reference
Richmond	0.013	44	5.24×10^{-2}	56.3	0.58	0.76	0.18	[2,3]
Richmond	0.025	44	5.24×10^{-2}	56.3	0.58	0.76	0.18	[2,3]
Hammermill A	0.343	14	2.03×10^{-1}	75.6	5.63	0.69	2.52	[8]
Appleton (East)	0.125	24	8.16×10^{-2}	63.6	1.55	0.75	0.52	[1]
Appleton (West)	0.125	24	2.71×10^{-2}	54.5	1.80	0.87	0.27	[7]
Appleton (West)	0.125	40	4.52×10^{-2}	54.5	1.78	0.86	0.29	[7]
Appleton (West)	0.125	64	7.23×10^{-2}	54.5	1.75	0.85	0.32	[7]
Odessa	0.241	10	8.52×10^{-2}	70.2	2.93	0.64	1.66	[7]

TABLE 12. COEFFICIENT AND EXPONENT VALUES FOR THE THROUGHPUT/HOLDUP RELATION $\dot{m} = a_1 H^{b_1}$ FOR VARIOUS HAMMERMILLS

Hammermill	Grate Opening, D_o (m)	Number of Hammers, N_H	Coefficients a_1	b_1	Correlation Coefficient	Data Reference
Richmond	0.013	44	0.039	0.95	0.96	[2,3]
Richmond	0.025	44	0.085	0.94	0.84	[2,3]
Hammermill A	0.343	14	0.010	1.49	0.92	[8]
Appleton East	0.125	24	0.49	1.03	0.85	[1]
Appleton West	0.125	24	2.58	0.53	0.91	[1]
Appleton West	0.125	40	0.55	0.80	0.93	[7]
Odessa	0.241	10	0.53	0.85	0.91	[7]

Of the machine parameters that were considered and defined in the present study to influence the relation between throughput and mill holdup, the predominant parameters were identified as total hammer volume (V_H), mill open volume (V_o), hammer tip speed (S), and the grate opening dimension (D_o). In particular, for the exponent b_1, the key parameters were chosen to be V_H, S, and V_o. The parameters D_o and V_o were chosen as the machine parameters that influence the coefficient a_1.

By noting that the exponent b_1 shown in Table 12 is positive for all of the mills that were studied and by assuming that it may be represented in terms of V_H, S, and V_o, reasoning suggests that increases in hammer volume or hammer tip speed should promote higher throughputs due to an increase in the number of hammer-particle collisions, while an increase in open volume should retard throughput, the latter occurring due to less hammer impacts per unit mass of material. The ordering of the terms, $V_H S/V_o$, reflects the above reasoning.

The relation for the exponent b_1 was found to be best represented by the following equation,

$$b_1 = 0.58 \exp [2.13 V_H^2 S/V_o] \quad (10)$$

where: V_H = total hammer volume (m^3)

S = tip speed (m/s)

V_o = open volume m^3

The correlation coefficient for Equation 10 is 0.90.

Likewise the coefficient a_1 was found to be positive for the hammermills listed in Table 12. Consequently, if a_1 increases, the throughput will increase also. To reflect the above trend in terms of D_o and V_o, a_1 must be proportional to D_o since increasing the grate opening decreases the resistance to the passage of material; hence, $\dot{m}$ increases. Conversely, the coefficient a_1 must be inversely proportional to V_o since greater open volume implies less hammer-particle collisions and therefore less size reduction and concomitantly a lower throughput. In addition to dependence upon D_o and V_o, the magnitude of the coefficient a_1 was also found to depend upon the value of the exponent b_1, and therefore a_1 exhibits a dependence upon V_H and S.

The relation of best fit for the the coefficient a_1 was found to be,

$$a_1 = 20.62 \left(\frac{D_o}{V_o}^{0.75} \right)^{2.16} \tag{11}$$

where: D_o = grate opening (m)

V_o = mill open volume (m^3)

The correlaton coefficient for Equation 11 is 0.93.

Power/Mill Holdup Relation

The work of previous researchers [1,2,3] has established a relation between the net power draw (P_N) required for size reduction and mill holdup (H^*). In its general form the relation takes the form,

$$P_N = a_2 \, H^{*b_2} \tag{12}$$

where a_2 and b_2 are numerical constants. The present study extended the usefulness of the relation represented by Equation 12 to a number of hammermills. As shown in Table 13, relatively high correlation coefficients were obtained for the hammermills that were studied.

In the process of developing the relation of power draw to holdup, extensive analysis and curve fitting established that the exponent b_2 could be characterized in terms of tip speed (S) and mill open volume (V_o), b_2 being proportional to both. The coefficient a_2 was found to be proportional to open volume fraction (V^*) and inversely proportional to tip speed (S) and total hammer volume (V_H),

$$b_2 = 0.7 \exp (0.071 \, SV_o) \tag{13}$$

The correlation coefficient for Equation 13 is 0.96.

TABLE 13. COEFFICIENT AND EXPONENT VALUES FOR THE POWER/HOLDUP RELATION $P = a_2 H^{*\, b_2}$ FOR VARIOUS HAMMERMILLS

Hammermill	Grate Opening, D_o (m)	Number of Hammers, N_H	Coefficients a_2	b_2	Correlation Coefficient	Data Reference
Richmond	0.025	44	1.68	0.95	0.92	[2,3]
Hammermill A	0.343	14	0.002	1.97	0.98	[8]
Appleton East	0.125	24	1.26	0.98	0.96	[1]
Appleton West	0.125	24	5.3	0.69	0.87	[7]
Appleton West	0.125	40	1.75	0.86	0.99	[7]
Odessa	0.241	10	0.41	1.04	0.87	[7]

As was the case in the development of the throughput/holdup relations in terms of the constant of proportionality (i.e., the coefficient "a"), a good agreement between the theoretical calculations and experimental results was achievable only if b_2 was incorporated into the expression for a_2. Thus, a_2 is in reality a function of V^*, V_o, V_H, and S. The relation for a_2 is given below,

$$a_2 = 9.4 \left(\frac{V^*}{SV_H}\right)^{1.36\, b_2} \tag{14}$$

The correlation coefficient for Equation 14 is 0.99.

Energy/Product Size Relations

A general result of previous work reported by Savage and Shiflett [1] is an empirical relation between specific energy requirements (E_o) and the characteristic size of the shredded product (X_o),

$$E_o = 17.91\, X_o^{-0.90} \tag{15}$$

where the units of E_o and X_o are, respectively, kWh/Mg and cm.

Equation 15 is an analytical fit to averages of data that had been collected from five hammermills of varying sizes while processing MSW over a wide range of operating conditions. Averaging the data necessarily diminishes the influence of throughput on particle size (and therefore on specific energy) for a particular shredder. This point can be elucidated by examining Figure 19 wherein is plotted the curve represented by Equation

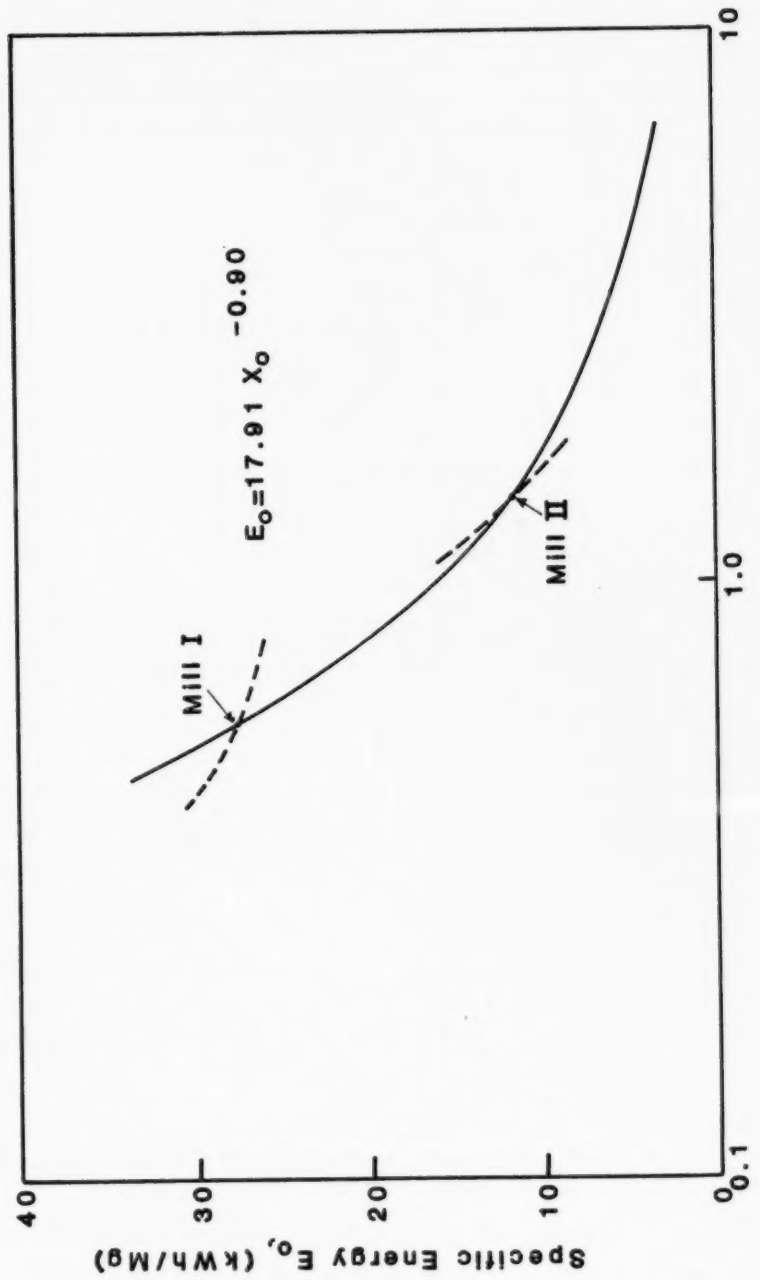


Figure 19. Specific energy as a function of product size.

15. Superimposed on the curve are hypothetical curves (dashed lines) that represent the specific energy/product size relation for hypothetical hammermills I and II. The hypothetical curves show the performance of the mills within their operating ranges of throughput. Inherent in the slope of the curves is the fact that for each mill the product size decreases as the throughput increases.

As part of the study, the specific energy/product size relation for particular shredders was investigated for the purpose of identifying machine parameters that contribute to the size reduction of material and, therefore, that influence the specific energy that is required. In other words, a hardware-oriented means was sought to identify the factors responsible for the slope of the dashed curves for the mills shown in Figure 19.

The logic for attempting to relate the specific energy requirement to characteristic particle size follows from two findings. First of all, previous studies [4,5,6,] have shown that shredded MSW conforms to the Rosin-Rammeler equation, i.e.,

$$y = 1 - \exp\left(-\left(\frac{x}{X_o}\right)^n\right) \tag{16}$$

where: n = distribution modulus

X_o = characteristic particle size

y = cummulative mass fraction passing particle size x

x = particle size

Secondly, previous studies [5,6] have shown that for a given shredder the range of n is narrow. Thus, the particle size distribution (defined by Equation 16) as a first order approximation can be solely characterized by the characteristic particle size, X_o.

Mention is also made of the fact that in the development represented here, the product size is considered independent of the particle size and composition of the raw waste feedstock, an assumption that is justified in the opinion of the authors for the purpose of assessing the impact of machine parameters on shredder performance.

To maintain similarity with the form of Equation 15, in the present study the machine-specific relations for E_o and X_o were cast in the general form,

$$E_o = a_3^* X_o^{-b_3^*} \tag{17}$$

or alternatively in terms of the format for the numerical entries required for the curve fitting studies,

$$E_o = a_3 \left(\frac{2.54}{X_o}\right)^{b_3} \quad (18)$$

where E_o and X_o have units of kWh/Mg and cm, respectively. The values of a_3 and b_3 for four different hammermills are given in Table 14. In addition, for the Appleton West hammermill values of a_3 and b_3 are presented for different operating configurations, i.e., hammer complements of 24, 40, and 64 hammers.

Table 14. COEFFICIENT AND EXPONENT VALUES FOR THE SPECIFIC ENERGY/PRODUCT SIZE RELATION $E_o = a_3\left(\frac{2.54}{X_o}\right)^{b_3}$ FOR VARIOUS HAMMERMILLS

Hammermill	Grate Opening, D_o (m)	Number of Hammers, N_H	Coefficients a_3	b_3	Correlation Coefficient
Richmond	0.025	44	0.41	2.6	0.95
Appleton East	0.125	24	2.29	0.11	0.86
Appleton West	0.125	24	4.00	0.38	0.85
Appleton West	0.125	40	4.47	0.12	0.60
Appleton West	0.125	64	5.17	0.53	0.98
Odessa	0.241	10	2.47	0.40	0.98

An extensive analysis of possible combinations of machine parameters that potentially could affect the magnitude of a_3 and b_3 resulted in the establishment of the ratio V_oD_o/SV_c as a significant term for characterizing a_3, and the product $V*D_o$ for characterizing the magnitude of b_3. The complete relation for a_3 is,

$$a_3 = 751\left(\frac{V_oD_o}{SV_c}\right)^{1.12} \quad \text{for} \quad \frac{V_oD_o}{SV_c} \leq 0.0127 \quad (19)$$

and

$$a_3 = 0.011\left(\frac{V_oD_o}{SV_c}\right)^{-1.44} \quad \text{for} \quad \frac{V_oD_o}{SV_c} > 0.0127 \quad (20)$$

The correlation coefficient for Equations 19 and 20 is 0.99. The complete relation for b_3 is,

$$b_3 = -6.32 - 2.34 \ln [(V^*)^{a_3} D_o] \quad \text{for } (V^*)^{a_3} D_o \leq 0.065 \qquad (21)$$

and

$$b_3 = 4.23 + 1.49 \ln [(V^*)^{a_3} D_o] \quad \text{for } (V^*)^{a_3} D_o > 0.065 \qquad (22)$$

The correlation coefficients for Equations 21 and 22 are 0.99 and 0.93, respectively.

Empirical relations for throughput and holdup and for power draw and holdup as a function of certain machine parameters were developed in a relatively uncomplicated manner. However, the development of a relation between product size and specific energy has lead to a set of a relatively complicated expressions, which are difficult to interpret.

Number of Hammers

The effect of the number of hammers on MSW shredder performance has not previously been studied. Consequently, one of the objectives of this program of investigation was to determine the relation (if any) between the number of hammers and shredder performance parameters. The test programs at the Appleton West and Odessa sites were designed to accommodate this objective. It is to be noted that because internal designs vary, it is often difficult to compare data obtained from one shredder with that obtained from another.

In June 1981, the Newell hammermill at Odessa was tested with a 10 and 14 hammer complement. This was followed by tests on the Allis Chalmers hammermill at Appleton West in July 1981 using 24, and then 40, and 64 hammers. Summaries of the performance data collected and derived from these tests are given in Appendices B and C.

Analysis of the data indicated that there was no apparent relation between the number of hammers and specific energy. However, relations between the number of hammers and characteristic particle size, freewheeling power, and net power were found.

Particle Size--

Relations between particle size and number of hammers were found for the Appleton West tests. No such relations could be determined for the Odessa data.

Figure 20 shows particle size as a function of throughput and number of hammers for the Appleton West shredder fitted with a grate having 12.7 x 30.5 cm grate spacing. As shown in the figure, product particle size decreases with increases in throughput. As the number of hammers is increased, the product size tends to decrease for throughputs in excess of 20 Mg/h. These trends have been developed by interpolation of the data for each hammer configuration.

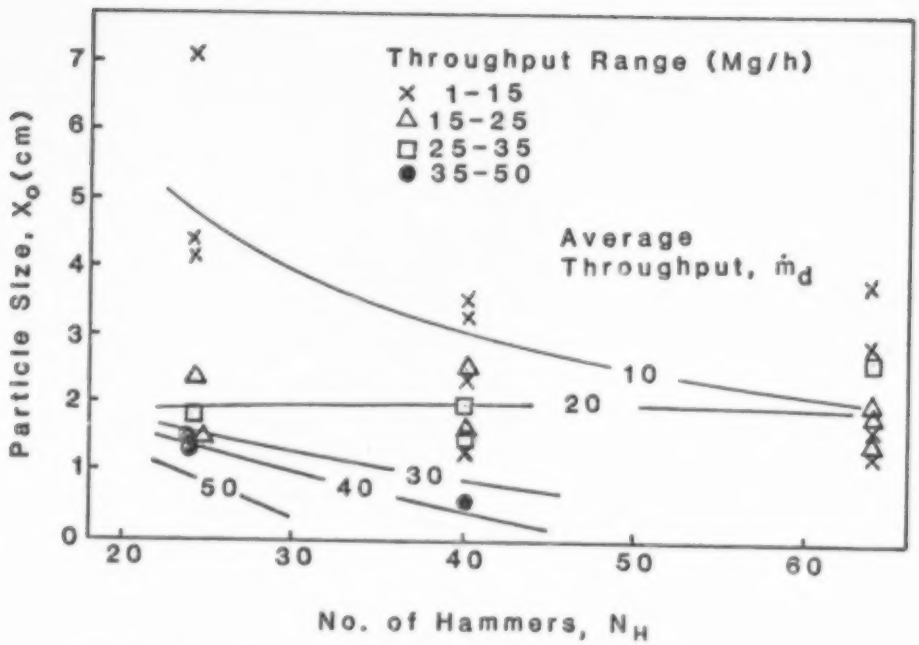


Figure 20. Particle size as a function of number of hammers and average throughput (Appleton West).

Freewheeling Power--

Freewheeling power was found to increase with an increase in the number of hammers. For the Odessa shredder (Figure 21), increasing the number of hammers from 10 to 14 increased the freewheeling power by more than 15 percent. Increasing the number of hammers from 24 to 40 at the Appleton West shredder (Figure 22) produced no observable increase in freewheeling power usage. However, an increase from 40 to 64 hammers increased the freewheeling power requirement by approximately 8 percent. The increase in freewheeling power requirement does not significantly affect the gross power requirements. However, if the operation and performance of the shredder are not impaired, the use of as few hammers as necessary represents a potential means of reducing energy consumption.

Net Power--

As shown in Figures 23 and 24, net power requirement for the Odessa and Appleton West mills was found to increase with throughput for all hammer complements, and decrease with an increase in the number of hammers. An increase in the number of hammers from 24 to 64 hammers on the Appleton West mill decreased net power (and the specific energy requirement) by as much as 30 percent.

Performance--

During the test series at Odessa and Appleton in which the minimum number of hammers were used (10 and 24, respectively), the mills operated satisfactorily from the standpoint of maintaining throughput capacity and particle size as required by the shredder operators. At the conclusion of the Odessa test, the plant re-installed 14 hammers in the shredder. At the conclusion of the Appleton tests, the plant left the 24 hammer complement in the machine and operated for a number of months with satisfactory performance.

Use of Relations for Estimating Performance

The relations that were previously defined and developed using data from a number of different shredders (e.g., throughput/holdup, power/holdup, and specific energy/product size) may be used by designers and operators to ascertain the consequences (i.e., changes in machine performance) that result from incremental changes in one or more machine parameters. For relations developed from data for a particular shredder the consequence of varying parameters such as the number of hammers, grate opening or open volume fraction may be estimated for design and operating conditions that are near those used to develop the relations. The range over which the relation for a particular shredder remains accurate must be determined through testing.

Equations 9, 12, and 18 and the equations for their respective coefficients and exponents may be used for shredder optimization once an operating setpoint has been determined. For example, once a throughput or product size constraint has been established, the appropriate relations may be used to establish whether or not the machine parameters are appropriate for obtaining the maximum performance (e.g., low energy consumption).

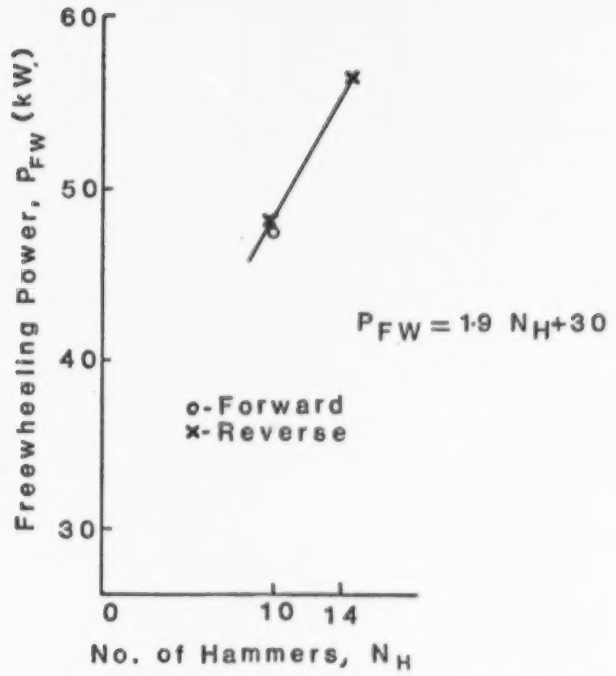


Figure 21. Freewheeling power as a function of number of hammers (Odessa).

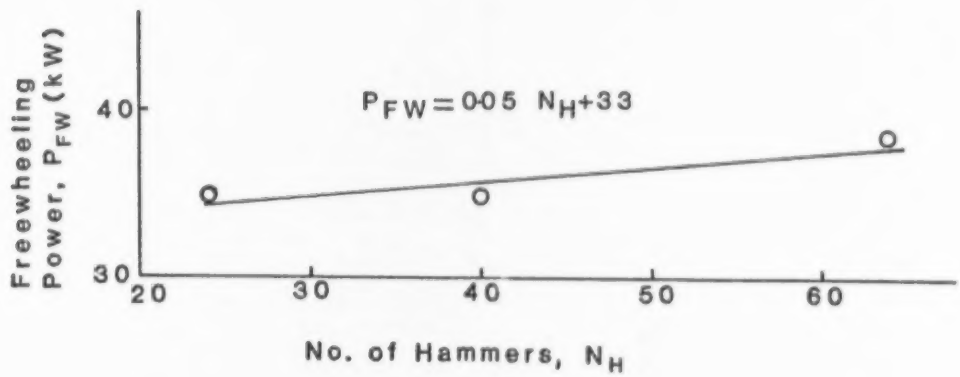


Figure 22. Freewheeling power as a function of number of hammers (Appleton West).

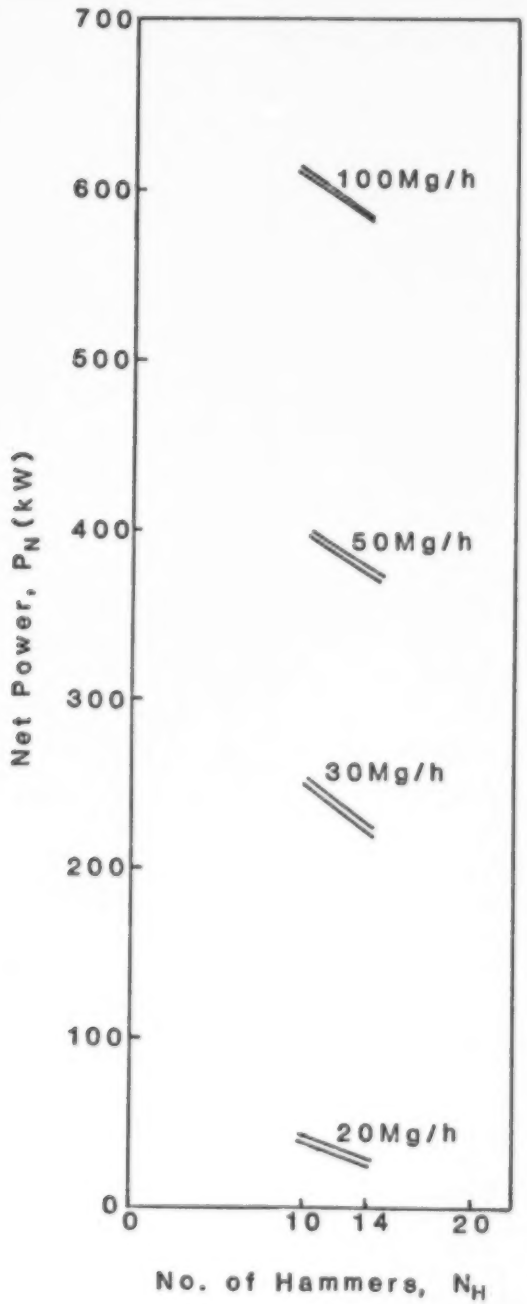


Figure 23. Net power as a function of number of hammers and average throughput (Odessa).

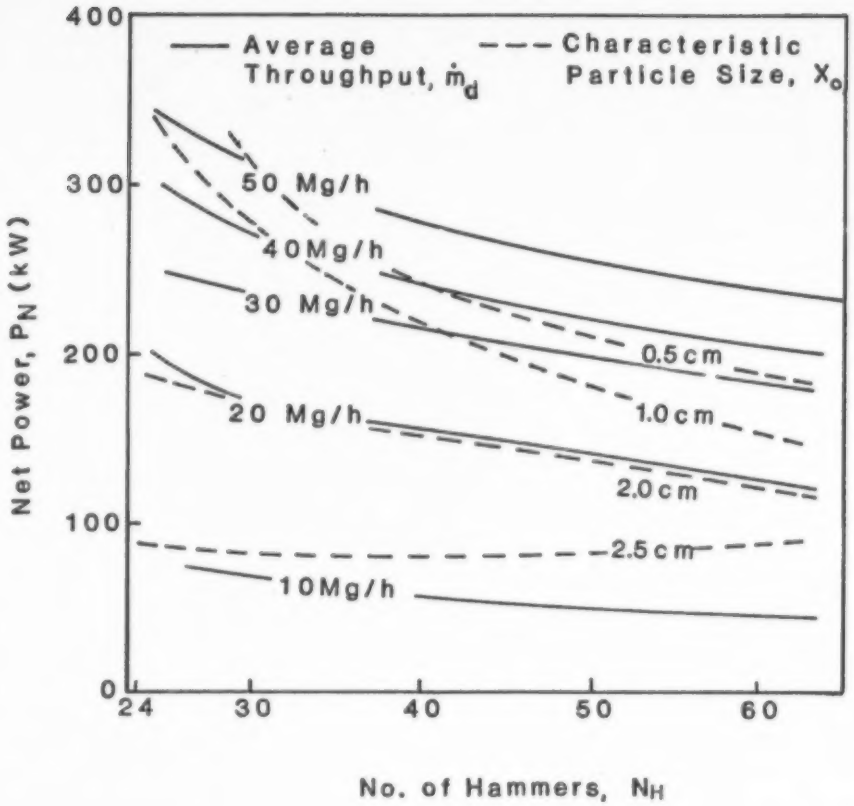


Figure 24. Net power as a function of number of hammers and average throughput (Appleton West).

Due to the empirical development of Equations 9, 12, and 18, their predictive capability rests within the bounds of the machine parameters that were used in the development of the relations. The parameters and ranges are listed in Table 15.

TABLE 15. APPLICABLE RANGE OF MACHINE PARAMETERS OF HORIZONTAL HAMMERMILLS FOR EQUATIONS 9, 12, AND 18

Grate spacing (D_O)	0.013 m	to	0.343 m
Total hammer volume (V_H)	0.0272 m^3	to	0.2026 m^3
Total swept volume (V_S)	0.765 m^3	to	8.15 m^3
Percent open volume ($V_O/(V_O + V_C)$)	63.5	to	86.9
Hammer tip speed (S)	54.5 m/s	to	75.6 m/s
Product size (X_O)	7.4 mm	to	140 mm

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8. Proprietary data source.

APPENDIX A

RICHMOND SHREDDER PERFORMANCE DATA

Site: Richmond, California

Date: October 1981

Equipment: Allis-Chalmers Gruendler
Grate Spacing: 10.2 x 10.2 cm
No. of Hammers: 44

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
1-1	4.7	3.9	18	14.0	68.6	28.2	40.4	8.6	10.5	2.0	5.8	0.86
1-2	1.8	1.5	18	2.6	40.0	25.3	14.7	8.2	10.0	2.1	4.8	0.85
1-3	1.0	0.8	18	3.5	34.3	25.3	9.0	9.0	11.0	2.5	6.0	0.82
1-4	0.9	0.7	18	5.8	28.2	25.3	2.9	3.2	3.9	2.5	7.0	0.82
1-5	6.2	5.1	18	5.5	80.0	25.3	54.7	8.8	10.7	1.5	3.6	0.89
1-6	7.9	6.5	18	29.1	160.0	25.3	134.7	17.1	20.9	1.5	3.8	0.89
1-7	7.0	5.7	18	29.1	120.0	25.3	11.6	13.5	16.5	1.6	4.1	0.89

(Continued)

RICHMOND SHREDDER PERFORMANCE DATA (Continued)

Site: Richmond, California

Date: October 1981

Equipment: Allis-Chalmers Gruendler
Grate Spacing: 5.1 x 10.2 cm
No. of Hammers: 44

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
2-1	3.0	2.5	18	5.5	36.9	25.3	11.6	3.9	4.8	0.7	2.0	0.65
2-2	0.5	0.4	16	1.6	28.2	25.3	2.9	5.8	6.9	0.9	2.1	0.55
2-3	0.3	0.3	12	0.7	26.7	25.3	1.4	4.7	5.3	1.5	2.4	0.25
2-4	9.2	7.5	18	69.5	200.0	25.3	174.7	19.0	23.2	0.6	1.2	0.70
2-5	8.8	7.1	19	53.8	187.5	25.3	162.2	18.4	22.7	0.7	1.3	0.65
2-6	3.6	2.9	20	22.6	75.0	25.3	49.7	13.8	17.3	0.9	1.5	0.55
2-7	4.4	3.6	18	11.8	57.1	25.3	31.8	7.2	8.8	0.8	1.8	0.60
2-8	6.3	5.1	19	19.3	60.0	25.3	34.7	5.5	6.8	0.7	2.0	0.65

(Continued)

RICHMOND SHREDDER PERFORMANCE DATA (Continued)

Site: Richmond, California

Date: November 1981

Equipment: Allis-Chalmers Gruendler
Grate Spacing: No grates used
No. of Hammers: 44

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
3-1	1.7	1.3	24	0.7	30.0	28.2	1.8	1.1	1.4	11.5	25.0	0.18
3-2	2.0	1.4	30	6.2	30.0	28.2	1.8	0.9	1.3	9.3	16.0	0.34
3-3	5.0	4.1	19	7.3	30.0	28.2	1.8	0.4	0.5	8.3	16.0	0.41
3-4	7.1	5.0	30	14.5	32.0	28.2	3.8	0.5	0.7	4.8	12.5	0.66
3-5	4.3	3.3	23	25.5	28.2	26.6	1.6	0.4	0.5	8.3	18.0	0.41
3-6	10.4	7.6	27	27.2	34.3	26.6	7.7	0.7	1.0	9.0	20.0	0.36
3-7	12.8	9.1	29	63.2	36.9	26.6	10.3	0.8	1.1	9.1	16.5	0.35

(Continued)

RICHMOND SHREDDER PERFORMANCE DATA (Continued)

Site: Richmond, California

Date: November 1981

Equipment: Allis-Chalmers Gruendler
Grate Spacing: 5.1 x 10.2 cm
No. of Hammers: 44

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
4-1	2.1	1.7	21	14.8	53.3	25.3	28.0	13.3	16.8	1.3	2.6	0.85
4-2	2.5	2.1	18	10.6	60.0	30.0	30.0	12.0	14.6	1.1	2.4	0.87
4-3	6.1	4.8	22	47.7	142.9	28.2	114.7	18.8	24.1	0.7	1.7	0.92
4-4	7.7	6.2	19	42.0	200.0	25.3	174.7	22.7	28.0	1.0	2.1	0.88
4-5	1.8	1.5	19	11.4	40.0	25.3	14.7	8.2	10.1	1.0	1.9	0.88
4-6	0.3	0.2	21	0.2	26.7	24.0	2.7	9.0	11.4	1.8	3.0	0.79
4-7	8.8	7.0	21	35.0	200.0	25.3	174.7	19.9	25.2	1.0	2.4	0.88
4-8	0.2	0.2	16	0.2	26.7	25.3	1.4	7.0	8.3	2.0	2.8	0.77

APPENDIX B

APPELTON WEST SHREDDER PERFORMANCE DATA

Site: Appleton West, Wisconsin

Date: July 1981

Equipment: Allis-Chalmers Model KH 12/18
Grate Spacing: 12.7 x 30.5 cm
No. of Hammers: 24

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
24-1	57.4	43.7	23.8	152.2	175.2	34.6	140.6	2.4	3.2	1.4	5.9	0.90
24-2	32.1	21.3	33.7	26.3	133.7	34.6	99.1	3.1	4.7	2.4	12.4	0.83
24-3	52.0	40.2	22.7	534.3	350.4	34.6	315.8	6.1	7.9	1.5	5.9	0.89
24-4	7.7	6.2	19.5	22.3	59.1	34.6	24.5	3.2	4.0	4.2	9.3	0.70
24-5	8.7	5.8	33.8	15.4	60.5	34.6	25.9	3.0	4.5	4.4	9.9	0.69
24-6	32.6	20.7	36.6	135.4	236.3	34.6	201.7	6.2	9.7	1.5	7.3	0.89
24-7	9.9	8.0	19.6	25.5	118.2	34.6	83.6	8.4	10.5	7.1	10.1	0.49
24-8	40.9	26.2	36.0	206.2	247.9	34.6	213.3	5.2	8.1	1.9	5.5	0.86

(Continued)

APPLETON WEST SHREDDER PERFORMANCE DATA (Continued)

Site: Appleton West, Wisconsin

Date: July 1981

Equipment: Allis-Chalmers Model KH 12/18
Grate Spacing: 12.7 x 30.5 cm
No. of Hammers: 40

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	C (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
40-1	32.1	24.8	22.6	211.6	203.2	34.9	168.3	5.2	6.8	2.5	7.8	0.82
40-2	17.4	13.2	24.3	149.8	181.5	34.9	146.6	8.4	11.1	2.4	7.1	0.83
40-3	50.3	38.0	24.4	101.9	220.9	34.9	186.0	3.7	4.9	0.7	3.7	0.95
40-4	37.4	25.4	32.1	156.8	267.4	34.9	232.5	6.2	9.2	2.0	6.4	0.86
40-5	45.2	32.0	29.2	292.2	267.4	34.9	232.5	5.1	7.3	1.6	5.1	0.89
40-6	1.9	1.6	15.6	7.1	43.4	34.9	8.5	4.5	5.3	3.4	9.2	0.76
40-7	19.5	12.5	36.1	12.7	68.7	34.9	33.8	1.7	2.7	1.4	5.1	0.90
40-8	2.5	1.9	23.7	11.7	49.8	34.9	14.9	6.0	7.8	3.5	6.6	0.75
40-9	25.5	19.3	24.5	83.5	87.6	34.9	52.7	2.1	2.7	1.7	7.0	0.88

(Continued)

APPLETON WEST SHREDDER PERFORMANCE DATA (Continued)

Site: Appleton West, Wisconsin

Date: July 1981

Equipment: Allis-Chalmers Model KH 12/18
Grate Spacing: 12.7 x 30.5 cm
No. of Hammers: 64

Test	$\dot{M}_w$ (Mg_w/h)	$\dot{M}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
64-1	36.3	23.9	34.2	75.2	181.5	38.5	143.0	3.9	6.0	1.6	6.9	0.89
64-2	47.0	32.7	30.4	101.4	191.7	38.5	153.2	3.2	4.7	2.6	9.6	0.81
64-3	32.6	20.5	37.0	39.2	141.1	38.5	102.6	3.2	5.0	1.9	6.6	0.86
64-4	4.8	3.6	24.2	21.5	66.9	38.5	28.4	5.9	7.9	1.7	5.0	0.88
64-5	2.8	2.1	26.0	14.2	64.3	38.5	25.8	9.2	12.3	1.3	5.8	0.91
64-6	30.8	20.8	32.6	103.6	199.3	38.5	160.8	5.2	7.7	2.1	6.1	0.85
64-7	13.5	9.2	31.5	56.2	105.9	38.5	67.4	5.0	7.3	2.9	10.0	0.79
64-8	15.9	11.8	26.0	129.7	141.1	38.5	102.6	6.4	8.7	3.8	11.0	0.73

APPENDIX C

ODESSA SHREDDER PERFORMANCE DATA

Site: Odessa, Texas

Date: June 1, 1981

Equipment: Newell Model 68
Grate Spacing: 35.6 x 24.1 cm
No. of Hammers: 10

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
10-1F	32.0	24.4	23.8	72.6	89.8	47.3	42.5	1.3	1.7	2.6	-	0.81
10-2F	22.8	18.2	20.0	16.3	80.2	47.3	32.9	1.4	1.8	5.3	9.3	0.62
10-3F	35.3	30.5	13.5	172.8	322.7	47.3	275.4	7.8	9.0	2.9	-	0.79
10-4F	29.2	21.9	25.0	71.7	72.6	47.3	25.3	0.9	1.2	5.9	-	0.58
10-5F	57.8	43.1	25.5	435.9	359.0	47.3	311.7	5.4	7.2	8.6	-	0.38
10-6F	25.4	21.3	16.2	26.3	271.2	47.3	223.9	8.8	10.5	9.0	-	0.36
10-7F	11.9	9.7	18.8	406.9	241.6	47.3	194.3	16.3	20.0	1.7	-	0.88

(Continued)

ODESSA SHREDDER PERFORMANCE DATA (Continued)

Site: Odessa, Texas

Date: June 2, 1981

Equipment: Newell Model 68
Grate Spacing: 35.6 x 24.1 cm
No. of Hammers: 10

Test	$\dot{M}_w$ (Mg_w/h)	$\dot{M}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{O_w} (kWh/Mg_w)	E_O (kWh/Mg_d)	X_O (cm)	X_{90} (cm)	Z_O
10-8R	20.4	15.2	25.4	183.3	61.6	48.3	13.3	0.7	0.9	4.4	9.1	0.69
10-9R	16.7	12.8	23.2	41.7	69.3	48.3	21.0	1.3	1.6	1.5	8.3	0.89
10-10R	58.7	44.7	23.8	320.7	369.4	48.3	321.1	5.5	7.2	5.3	-	0.62
10-11R	-	-	-	-	-	-	-	-	-	-	-	-
10-12R	31.0	23.2	25.3	272.6	67.4	48.3	19.1	0.6	0.8	2.2	-	0.94
10-13R	190.5	138.3	27.4	859.6	670.8	48.3	622.5	3.3	4.5	1.3	4.6	0.91
10-14R	31.3	23.3	25.7	396.0	167.7	48.3	119.4	3.8	5.1	4.3	-	0.69

(Continued)

ODESSA SHREDDER PERFORMANCE DATA (Continued)

Site: Odessa, Texas

Date: June 4, 1981

Equipment: Newell Model 68
Grate Spacing: 35.6 x 24.1 cm
No. of Hammers: 14

Test	$\dot{m}_w$ (Mg_w/h)	$\dot{m}_d$ (Mg_d/h)	MC (%)	H* (kg)	P_G (kW)	P_{FW} (kW)	P_N (kW)	E_{o_w} (kWh/Mg_w)	E_o (kWh/Mg_d)	X_o (cm)	X_{90} (cm)	Z_o
14-1R	33.2	24.0	27.7	816.5	254.9	56.1	198.8	6.0	8.3	2.4	-	0.83
14-2R	83.5	54.4	34.9	914.9	621.7	56.1	565.6	6.8	10.4	2.2	-	0.84
14-3R	30.6	22.0	28.0	344.3	344.5	56.1	288.4	9.4	13.1	2.7	6.6	0.81
14-4R	101.7	81.4	20.0	534.3	621.7	56.1	565.6	5.6	6.9	1.5	7.4	0.89
14-5R	47.6	38.3	19.5	498.1	238.2	56.1	182.1	3.8	4.8	1.8	-	0.87
14-6R	66.5	42.0	36.8	342.0	177.6	56.1	121.5	1.8	2.9	1.7	7.2	0.88
14-7R	36.1	24.5	32.1	413.7	303.4	56.1	247.3	6.9	10.1	2.4	9.4	0.83
14-8R	21.8	16.0	26.8	41.3	71.2	56.1	15.1	0.7	0.9	5.7	-	0.59

GLOSSARY

characteristic size: Screen size corresponding to 63.2 percent cumulative weight percent passing.

closed volume: Volume of internal shredder hardware.

degree of size reduction (Z_o): Defined by the ratio $(F_o-X_o)/F_o$. A dimensionless parameter used to describe the amount of size reduction occurring during shredding, e.g., $Z_o = 0$ imples no size reduction, $Z_o = 0.90$ implies characteristic product size, X_o, is equal to 0.10 F_o.

freewheeling power: Power requirement for conditions of zero throughput and hold-up.

grate opening: Dimension of the grate opening that is tangential to the circular path of the rotating hammers.

hammer volume: Total volume of all hammers.

machine parameters: Shredder design characteristics such as grate opening, number of hammers, internal open volume, etc.

MSW: Municipal solid waste.

nominal size: Screen size corresponding to 90.0 percent cumulative weight percent passing.

open volume: The difference between the swept and closed volumes.

open volume fraction: Open volume divided by swept volume.

shredder (or mill) holdup: Material in shredder at any instant in time.

specific energy: Net energy requirement (or consumption) expressed on the basis of net energy utilized per ton of waste shredded.

swept volume: Cylindrical volume defined by the tip-to-tip diameter of the rotating hammers and the length of the shredder shaft within the shredding zone.

throughput: Mass flow rate.

tons: In all cases, the word tons refers to metric tons (1000 kilograms).